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Durability of concrete beams with FRP wraps

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Durability of Concrete Beams with FRP Wraps

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ABSTARCT

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This research focuses on the durability of carbon FRP (CFRP) wraps bonded to concrete beams under accelerated and natural aging. Variation in mechanical properties of CFRP wrapped concrete beams due to aging through water immersion, salt and alkaline solution immersion at elevated and freeze-thaw temperature variation are studied. Different parameters evaluated during beam bending tests are: maximum load (moment), deflections, crack width, and deformability factor. Accelerated aging was carried out on 5”×8” ×60” wrapped beams under: 1) water immersion at room, 110°F and 140°F temperatures 2) alkaline and salt solution at room temperature 3) alkaline and salt solution at freeze-thaw temperature. In addition, 5”×6” ×96” and 6”×15” ×120” beams wrapped with CFRP fabrics were aged naturally to correlate the results of accelerated and natural aging.

Aging of CFRP wrapped concrete beams in water at elevated temperatures, average experimental load (moment) to theoretical load (moment) capacity of the wrapped concrete beams after 3, 6 and 9 months varied between 1.026 and 1.178. Results of experimental /theoretical load (moment) ratios indicated a trend of reduction in load (moment) capacity with increasing temperatures. Deflection limits of aged beams ($l/360$, $l/240$ and $l/180$) under different conditioning schemes were compared. Crack width limit (0.016in) under different conditioning schemes was also compared. Loads at limiting crack width showed reductions with increasing temperature and aging duration. CFRP strips were extracted from the wrapped beams subjected to bending tests after aging. All extracted CFRP strip specimens were tested in tension. Strength reduction in strips was a maximum of 12.9 % under 140°F water aging and stiffness reduction in strips was a maximum of 7.48 %.

Accelerated and natural aging results were compared on the basis of stress-temperature-time superposition principles. Based on the correlation of natural aging to accelerated aging, 12.9 % strength reduction in carbon wraps bonded to concrete beams is equivalent to about 82 years.

DEDICATION

This thesis is dedicated to my parents and wife for their moral support and appreciation shown in the completion of this research work.

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Chapter 1

INTRODUCTION

1.1 GENERAL REMARKS

Civil infrastructures, built with conventional steel reinforced concrete and exposed to hash environments have a service life about 50 years. A general problem with these structures is reinforcement corrosion and deterioration of concrete strength, primarily due to environmental exposure. One of the solutions to improve the strength and stiffness of deteriorated concrete structures is to use fiber reinforced polymer (FRP) composites because of their wide usage in other fields (CDDC 2002).

Research is being conducted in the use of FRP materials in construction for the past 15 years. FRPs are used as reinforcement in different types of concrete structures and also used for rehabilitation of distressed or deficient structural members. Repair and retrofit of concrete structures using composites are beneficial as compared to building new structures because of high replacement costs and productivity losses.

FRPs provide a valuable method for retrofitting and strengthening of damaged and deteriorated structures in terms of improving durability and strength in service structures. Many researchers (CDDC2002) have studied the behavior and properties of externally bonded FRP wraps on concrete members. However, durability of concrete members wrapped with FRPs is still not well established and needs additional research. Therefore, it is necessary to study the durability of FRP used as reinforcing or strengthening material in concrete members under chemical and thermal conditions including natural weathering. The results from this research are expected to contribute to the understanding and knowledge of the behavior of CFRP wrapped concrete beams, which are aged in different conditioning schemes.

1.2 OBJECTIVE

The main objective of this research is to study the durability of fiber reinforced polymer (FRPs) wraps bonded to concrete beams through accelerated and natural aging. Different aspects of this objective are:

- To establish the structural response (strength, stiffness and deformability) behavior of carbon fiber wrapped concrete beams through accelerated aging under:
  - Water immersion at room and elevated temperatures (110°F and 140°F temperature)
  - Alkaline and salt solution immersion at room temperature
  - Alkaline and salt solution immersion at freeze-thaw conditions
- To establish the structural response of carbon fiber wrapped concrete beams through natural aging
  - Constant 68 °F of room temperature
  - Natural weathering exposure
- To correlate the response data of accelerated and natural aging. Using tensile strength and stiffness data from FRP strips extracted from beams aged under different conditioning schemes

- To compare the accelerated aging to natural weathering data from another part on another part of bond between CFRP and concrete (Barger 2000).

Degradation in strength and mechanical properties of FRP wrapped concrete beams are studied under different temperatures, salt solution, alkaline solution and natural aging. Aging related reduction in the effectiveness of wrapped concrete members in terms of strength, stiffness, serviceability parameters (deflection, crack-width) and deformability factors are evaluated.

1.3 SCOPE

Concrete beams wrapped with carbon fiber sheets and carbon fiber coupons were subjected to accelerated and natural aging conditions. CFRP strips were extracted from wrapped beams that were aged and tested in tension. Different aging parameters used in this research are listed below.

1.3.1 Accelerated aging

Carbon fiber wrapped concrete beams and CFRP strips extracted from beams after beam bending test were aged under:

1. Water immersion at room and elevated temperatures with aging duration 3,6 and 9 months (16 beams and 60 strips).
2. Alkaline and salt solution immersion at room temperature for 3 months (8 beams and 12 strips).
3. Alkaline and salt solution immersion with freeze-thaw temperature variation in environmental chamber for 6 months (4 beams and 12 strips).

Note: It should be noted that the CFRP strips used for tension test in this research were prepared to meet tension test specifications and then aged or extracted from aged beams

1.3.2 Natural aging

Carbon fiber wrapped concrete beams and CFRP strips extracted from beams after beam bending test were aged under:

1. 68 °F without any change in temperature for 3.5 years (3 beams and 8 strips).
2. Natural weathering outside the Major Units Laboratory at West Virginia University for a period of three years (3 beams and 6 strips).

In addition, two more beams were tested without carbon wraps to establish base line values. Eight additional beams are currently being conditioned.

Altogether, 36 beams and 98 strips were tested during this research program.

1.3.3 Parameters evaluated and compared:

Beams: maximum load (moment), deflection, crack width and *deformability factor (explained in section 5.3.4)

Note: Deformability factor is defined as the ratio of energy absorption (or area under moment curvature or load-deflection curve) at ultimate to energy absorption at limiting curvature value (GangaRao and Vijay, 1998).

Strips: strength and stiffness

Temperature schemes: room temperature, 110°F temperature, 140°F temperature and freeze-thaw conditions

Aging duration: Accelerated aging: 3, 6 and 9 months

Natural aging: 14, 24, 36 and 42 months

Wrapping configuration: 1 longitudinal layer at the beam bottom

2 layers of longitudinal and U-shape wrapping

This report is organized into 9 chapters. Chapter 1 describes objectives and scope of this research. Chapter 2 deals with the literature review. Chapter 3 describes materials used in this research. Chapter 4 discusses test-set up, methods for wrapping concrete beams, and preparation of carbon fiber strips. Chapter 5 presents results of bending tests on aged beams and tension tests on carbon fiber strips. Analysis on degradation rates in terms of ultimate bending moment capacity, deflection, crack width and deformability are also discussed in chapter 5. Analysis of wrapped beams and coupon level specimens under natural aging are also presented in chapter 6. Correlation of natural and accelerated aging is carried out in chapter 7. Chapter 8 presents bending theory of carbon fiber wrapped concrete beams. Finally, chapter 9 provides some conclusions and suggestions for future research.

Chapter 2

LITERATURE REVIEW

2.1 INTRODUCTION

Many researchers have been interested in using FRP wraps as strengthening materials for the last 15 years. These advanced materials are considered due to their advantages in terms of strength to weight ratio, electrochemical corrosion, and availability in any length or shape, fatigue, chemical and environmental resistant properties. The numerous applications of FRPs in various fields such as automobile, recreation, sports and aerospace industries have led to significant decrease in cost of FRPs. This decrease in cost of FRPs along with the reduction in necessary maintenance costs makes the use of FRPs economically competitive as compared to conventional construction materials.

Presently, FRPs are extensively used in repair, retrofitting, rehabilitation and strengthening of infrastructure because of improvements in strength, ductility/deformability and durability (CDDC1998 and 2002). Durability issues of FRP wrapped concrete elements subjected to environmental and chemical exposure are not well understood. In addition, it is necessary to clearly understand the physical and mechanical properties of FRP wrapped concrete beams under different service conditions. Specifically, carbon fiber reinforced polymer (CFRP) wrapped beams are subjected to water immersion aging condition and pH variation at both coupon and component level should be well understood to have a better understanding of their (beams) aging.

2.2 REVIEW OF DURABILITY OF WRAPPED CONCRETE BEAMS

Thomson (1994) studied the freeze-thaw durability of concrete beams bonded with aramid, E-glass and graphite fabrics. The beams used in the test were 1.125 × 1.5 inches in cross section and 13 inch long and bonded with one layer of composites. The freeze-thaw cycle process (ASTM C 672-84) was used for aging. Calcium chloride solution, mixed in the ratio of 4 grams of calcium chloride to 100 milliliters of water was employed to immerse concrete beams. Each freeze-thaw cycle included 16 hours of freezing in solution followed by 8 hours of drying in air. After 50 and 100 cycles, the beams were tested in flexure test. The beam bonded with Aramid and E-glass fabrics showed 50% reduction in strength at the 100th freeze-thaw cycle. However, the beams bonded with graphite fabrics did not show any decrease in strength.

Soudki (1998) presented test results of reinforced concrete beams strengthened with CFRP sheets subjected to wet-dry condition. In his study, 8 reinforced concrete beams were pretested before the wet-dry process. The cracked beams were repaired with CFRP sheets while the other 3 beams without pretesting were used to compare the results from testing. For the test program, 8 beams immersed in deicing chemicals (2% NaCl) were subjected to wetting and drying process for 50, 100, 200 and 300 cycles respectively. In the wet-dry cycles, the concrete beams were alternately tested in wet condition for 24 hours and dry condition with blow heaters for 24 hours. All beams were tested to failure under four point bending test after the wet-dry process. From research results, little or no corrosion activity was noted in three of the beams after 50 wet-dry cycles. However, corrosion was active in specimens under 100 wet-dry cycles. In addition, minimal chloride ionic diffusion was found on FRP sheets.

Javed (1996) has studied aging behavior of research in concrete beams externally bonded with carbon fiber tow sheets. The research was conducted to study the effects of accelerated aging on stiffness and strength of concrete beams. In addition, bond pull-off tests have also been reported by Javed. Thirty-eight beams were externally bonded with carbon fiber tow sheet and tested as cantilever beams. The aging process consisted of constant and freeze-thaw temperature variation on wrapped beams, cylinders and bond pull-off samples. The temperatures ranged from -20° F to 120° F while humidity differed from 0 % to 100 %. The specimens were subjected to acidic and alkaline solutions of pH level 3 and 13, respectively. At the end of 5, 15 and 25 cycles, two specimens from each of the environmental conditions were removed to test them at room temperature for a week. The results from this research showed an increase in stiffness of externally bonded concrete beams, which were aged for 5 cycles when compared with control beams. However, it was found that the decrease in stiffness with respect to that of control beams was observed after 15 cycles of aging.

Homan (2000) studied the durability of fiber-reinforced polymer composites. His research presents the results of FRP coupons and FRP-FRP single lap bond specimens subjected to freeze-thaw cycling (50, 100, 200 and 300 cycles), UV radiation (1200, 2400, and 4800 hours), temperature variation (28, 56, 112 and 336 cycles), NaOH solutions with pH 10 and pH 12 concentrations (7,14, 28 and 84 days) and moisture (7,14, 28 and 84 days). From his results, it appears that the tensile property of coupons subjected to freeze-thaw cycles in the controlled laboratory environments were not significantly affected for CFRP and GFRP. While the strength of GFRP coupons decreased by a maximum of 7 percent after 84 days (320 cycles) of exposure to both pH10 and pH 12 NaOH solutions at 22° C. The effect of temperature variation between -20° C and + 40° C presented no degradation in mechanical properties of CFRP.

Kshirsagar (1998) studied the FRP-wrapped concrete cylinders under accelerated environmental aging. The influence of six different accelerated aging conditions was examined on the durability of cylinders wrapped with a single layer of a glass fabric embedded in an epoxy matrix. After 1000, 3000 and 8000 hours of aging, specimens were tested in compression. The wrapped concrete cylinders under either hot liquid media or extended freeze-thaw cycling have deteriorated. In addition, combined effect of cycling and the strengthening of FRP wraps was significantly lost after 3000 hours of aging.

Green (1998) studied the effects of freeze-thaw on bond between FRP sheets and concrete. Beams were strengthened with both glass and carbon fiber sheets. Those beams were aged under 50, 150 and 300 cycles of freeze-thaw exposure. The beams were tested to failure under 4 point bending after the end of exposure. The results did not show any degradation to bond at the concrete/FRP interface under freeze-thaw conditioning.

Micelli (2002) presented experimental results of FRP confined concrete cylinders subjected to accelerate environmental exposure. Glass and carbon unidirectional sheets were used in this research. Two different conditioning agents were chosen. First, the specimens were immersed under a 15% in weight aqueous solution of NaCl for a total of 2880 hours. Second, the specimens were under freeze-thaw conditioning, high humidity, high temperature cycling and indirect UV exposure in an environmental chamber. GFRP and CFRP sheets wrapped on concrete cylinders increase the ultimate strength to 1.6 times that of plain concrete. GFRP wrapped cylinders under environmental cycles or immersion in NaCl solution showed a moderate decrease in ultimate strength and loss in ductility by about 40%. However, CFRP-wrapped cylinders under aging condition did not show a significant decrease in ultimate strength.

2.3 CONCLUSION

The effects of temperature, alkali, salt and freeze-thaw on the mechanical properties and serviceability of FRPs wrapped concrete beams need to be studied at both coupon and component levels. Research on effects of FRPs wrapped concrete elements under environment factors are not comprehensive regarding their serviceability, mechanical and physical properties of wrapped beams. Therefore, it is essential to study these effects on FRPs wrapped concrete beams.

Chapter 3

MATERIALS

3.1 INTRODUCTION

In order to study the behavior of FRP wrapped concrete beams, it is important to understand the properties and nature of the materials used in this research. Therefore, detailed material property description has been provided, herein.

3. 2 CONCRETE

The concrete used in this study was ready-mixed concrete Type I. It was supplied by Hoy REDI-MIX, Morgantown, WV. The compressive strength of concrete was generally 4000 psi. The concrete was poured in the formwork and removed after 24 hours. The concrete beams were cured by wet burlap, and plastic was placed over them for 28 day curing. Beams were cast in different batches and each batch comprised of at least 12 beams. Each beam was designated with its batch identification (A, B, C etc.) followed by the beam specimen number (1, 2, 3 etc.). Therefore, the beams in this study are designated A1, …, A12, B1, …, B12, etc. For each batch of beam casting, concrete was ordered from a single concrete plant with same mix specifications. For all the batches, average concrete cylinder strength (f_c') of 4 ksi was achieved with minor variation.

3. 3 STEEL

The steel employed for this research was conventional grade 60 reinforcement. It was used as a nominal reinforcement for all the concrete beams to obtain desired failure modes of fabric rupture / debonding. Adequate shear reinforcement was provided for all the beams.

3. 4 CARBON FIBER TOW SHEET

The Carbon Fiber Tow Sheet manufactured by Tonen Corporation, Japan was used for this research. Tow sheets were made of unidirectional fibers and supported on a glass fiber scrim. The Carbon Fibers stress-strain behavior is linearly elastic to failure. The carbon fibers are resistant to moisture, some solvents, bases and weak acids. Properties of carbon fiber tow sheet reported by manufacturer are shown below.

Design thickness based on a single uncoated fabric	0.004 inches (0.10 mm)
Tensile strength:	2.2 kip/inch (382N/mm)
Tensile Modulus:	33Msi (23.03×10^4 N/mm^2)
Ultimate strain:	1.5% or .015
Density:	0.056 lbs /in^3
Shear Modulus:	7687 ksi
Poisson Ratio:	0.28

3.5 PRIMER AND ADHESIVE

The adhesive known as the Mbrace epoxy resin was manufactured by Master Builders Technology Application. It was used to bond carbon tow sheets to the concrete surface. The method recommended by the manufacturer was used for wrapping.

Primer

Two –part primer A and B were mixed in 3:1 ratio, respectively by weight or volume. It was allowed to cure 24 hours after application to the concrete surface.

Adhesive

The adhesive was also in two parts mixed in 3:1 ratio by weight or volume. It was applied to the concrete surface as well as the fabric after the primer was cured for 24 hours.

3.6 PROCEDURE FOR WRAPPING CONCRETE BEAMS

The reinforced concrete beams were cast in formworks. Tension and shear reinforcement were available in every beam. Oil was applied to formwork surface after assembling. Before pouring concrete, the reinforcement position and beam dimension were checked and adjusted for accuracy in reinforcement position and dimension of beam. After pouring concrete, the top surface of the test beams was made smooth and the beams were covered with burlap. After removing from formworks, beams were cured at ambient temperature for 28 days. Beams were cleaned and sanded at the position that was to be bonded with carbon fiber Tow sheet. Before carbon fiber sheet was applied, the surface might be repaired by using mortar at the defected surface. In the next step, the prepared primer mix was applied to surface and allowed to cure. After that, the epoxy resin was mixed in the ratio 3:1 of resin and hardener and applied to carbon fiber Tow sheet. This carbon fiber Tow sheet was wrapped at position designated. To remove any possible air bubbles, the thin plastic plate was pressed along length of carbon fiber Tow sheet. The epoxy resin was re-applied on the carbon fiber wrapped surface. The same procedure was repeated for applying a new carbon fiber layer. The beams wrapped were left to cure at room temperature before beam aging procedure.

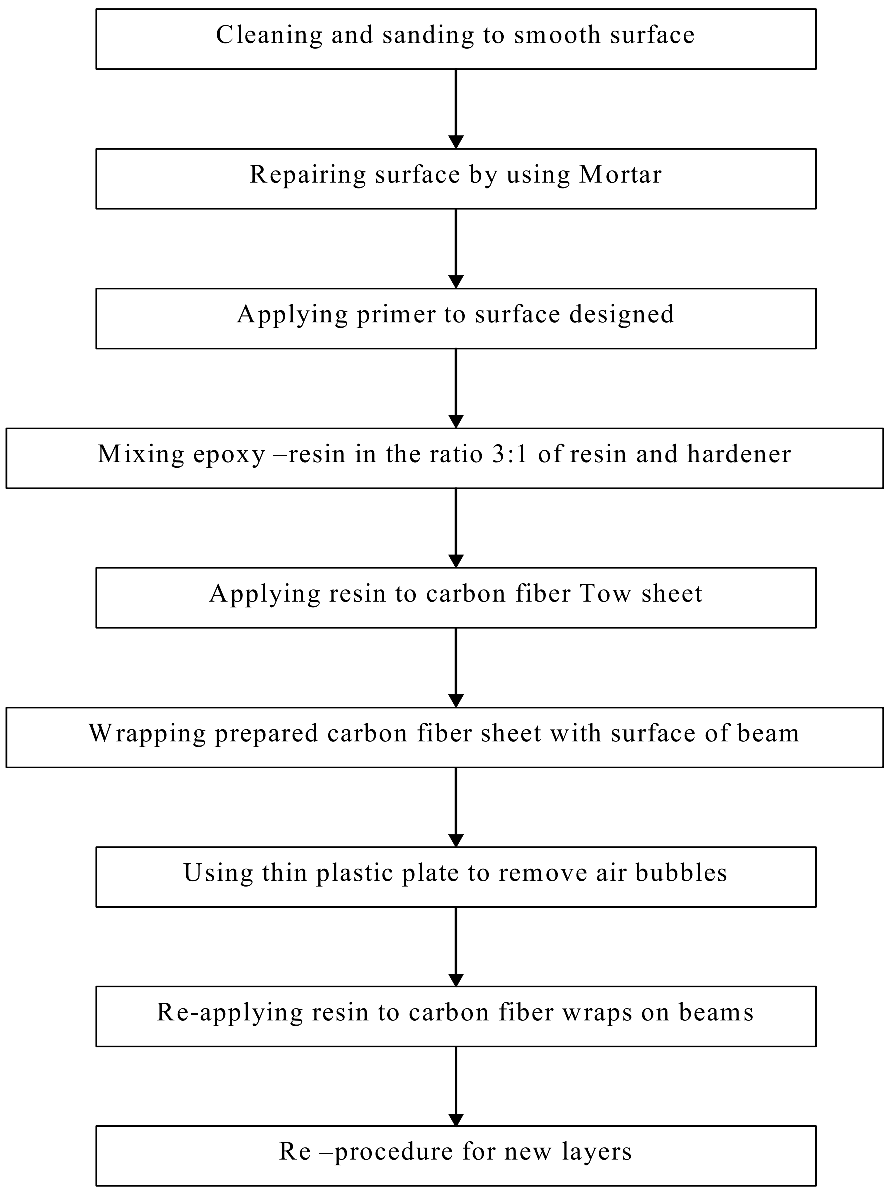

Fig 3.1 Wrapping procedure of carbon fiber sheet with reinforced concrete beams

Chapter 4

TEST SPECIMENS AND EXPERIMENTAL SET-UP

4.1 INTRODUCTION

This chapter discusses the test set up for carbon fiber wrapped concrete beam specimens. Smaller beam dimensions were chosen to physically accommodate them in the environmental chamber and larger beam dimensions were chosen for natural aging, where handling and dimensions were not a problem. Dimensions were also based on appropriate failure type, i.e., tension fabric rupture to evaluate the beam and wrap durability.

4.1.1Types of specimens

Type I specimens: concrete beams measuring 5”× 8” ×60” were reinforced with number 3 conventional steel reinforcement. Those beams were wrapped with a carbon tow sheet layer and aged under water immersion and chemical (alkaline and salt solution) immersion. Carbon fiber sheet extracted from wrapped concrete beams was tested after aging and beam bending test.

Type II specimens: concrete beams measuring 5”× 8”× 60” were reinforced with number 3 conventional steel reinforcement. Those beams were wrapped with carbon tow sheets in U shape and aged under alkaline and salt solutions at room and freeze-thaw conditions.

Type III specimens: concrete beams measuring 5”× 6”× 96” were wrapped with one (beam b1 and b3) and three (beam b2) carbon layers at the bottom of the beam. The beams were conditioned under constant 68° F without any change in temperature conditions.

Type IV specimens: concrete beams measuring 6”× 15” × 120” were wrapped with one layer on the tension side of the beams. Carbon fabrics were symmetrically bonded on either side of the centerline at beam bottom to a length of 3 ft (Beam NA-1), 4 ft (Beam NA-2), and 5 ft (Beam NA-3).

FRP strip specimens: aged and non-aged carbon fiber strips measuring 0.5 inch in width and 15 inches in length were obtained from carbon fiber wrapped beams and new coupon strips from undamaged carbon fiber sheet. Tension tests were conducted to evaluate the strength and stiffness of fiber strip specimens.

4.1.2 Aging scheme

Accelerated aging

Water immersion aging: Temperature tanks were prepared for immersing concrete beams (type I) at room, 110 °F and 140 °F temperature.

Chemical immersion aging, alkaline and salt solutions were used to aging beams (type I and II) at room and freeze-thaw temperature. Alkaline solution of pH~ 13 consisted of 97.4 % water (H_2O), 0.2 % Calcium Hydroxide ($CaOH_2$), 1.4 % Potassium Hydroxide (KOH), and 1% Sodium Hydroxide (NaOH) by weight. Salt Solution was obtained using 97 % water (H_2O) and 3 % Sodium Chloride (NaCL) by weight.

Natural aging

Concrete wrapped beams (type III) were under constant 68° F of room temperature without any change in temperature for 3.5 years. After aging, these beams were tested under three-point loading.

Concrete wrapped beams (type IV) were aged under outside weathering for 3 years. During each year of natural aging, the beams were subjected to freezing and thawing during winter (snow) season, high and low temperature variation during summer, and temperature variation coupled with humidity variation during rainy season. After each aging period (14, 24 and 36 months), the beams were brought back into the laboratory and the same four point bending tests were performed by loading them to 8,000 lbs (14 k-ft).

4.2 SPECIMEN DESCRIPTIONS

Thirty-six reinforced concrete beams were cast and cured for 28 days. Thirty-four beams were wrapped with carbon fiber tow sheets. Concrete beams aged under accelerated and natural aging were classified in Tables 4-1to 4-4-.

4.2.1 Water immersion aging at room and elevated temperatures

For water immersion at room and elevated temperatures (110°F and 140°F temperature), each temperature tank was composed of carbon fiber wrapped concrete beams (type I) immersed in water (H_2O) at room, 110°F and 140°F temperature ,respectively. The process of aging these beams took 3 to 9 months in three different temperature tanks. Three-point bending method was used to test these beams once every 3 months.

4.2.2 Alkaline and salt solution immersion aging at room and freeze-thaw conditioning

Carbon fiber wrapped concrete beams (type I and II) were immersed in both alkaline and salt solution tanks at room temperature. The duration of the process of aging was about 3 months in both tanks. Three-point loading method was used to test these beams.

In addition, four carbon wrapped concrete beams (type I and II) were aged under alkaline and salt solution at freeze-thaw conditions in environmental chamber until 6 months before testing them under three-point loading.

4.2.3 Natural aging at constant 68 °F of room temperature

For naturally aged beams of 5”×6”×96”(type III), beams b1, b2 and b3 wrapped with one, three, one layer of carbon fabric, respectively, were reinforced with 2#3 bars on compression side. They were aged under room temperature of 68 °F for 3.5 years. The beams were tested under three-point loading under different loading and unloading cycles.

4.2.4 Natural aging under constant 68 °F of room temperature

For naturally aged beams of 6”×15”× 120”(type IV), three beams were naturally aged outside and periodically tested for stiffness loss at the end of first, second and third years. During each year of natural aging, the beams were subjected to freezing and thawing during winter (snow) season, high and low temperature variation during summer, and temperature variation coupled with humidity variation during rainy season. After aging, the beams were brought back into the laboratory for 4-point bending test by loading them to 8000 lbs (14 k-ft).

Table 4-1 Concrete beams (5”× 8”× 60”) aged in water

Type	Age (months)	Beams under temperature aging		
		Room temperature	110 F temperature	140 F temperature
Type I specimens	3	B3 / B11	E11 / E12	A4 / A5
	6	B1 / B2	E3 / E4	D2 / D5
	9	B2 / B4 / B5	E1 / E2	D1 / D2 / D4

Table 4-2 Concrete beams (5”× 8”× 60”) aged under alkaline and salt solution

Type	Age (months)	Beams under chemical aging	
		Alkaline	Salt
Type I and II specimens at room temperature	3	A6 / A7 / A10 / A12	C2 /B9 /B6 /A9
Type I and II specimens at freeze-thaw temperature	6	C4 / C8	C1 / C10

Table 4-3 Concrete beams (5”× 6”× 96”) aged under constant 68 °F temperature

Type	Age (years)	Layer of carbon wrap	
		1 layer	3 layers
Type III specimens	3.5	b1 / b3	b 2

Table 4.4 Concrete beams (6”× 15”× 120”) aged under natural weathering for 3 years

Type	**Natural aging beams tested at 14, 24 and 36 months**		
Type IV specimens	**Length of carbon fiber wraps**		
	3ft	**4 ft**	**5 ft**
	NA -1	NA-2	NA-3

4.2.5 CFRP strip preparation

Unaged- CFRP strip specimens were prepared as a basis for comparison with those extracted from aged beams after respective beam bending tests.

Unaged CFRP strip specimens

Carbon tow sheet was cut to 18 inch in width × 15 inch in height with disposable cutter. Epoxy resin system, from Mbrace, base (part A) and hardener (part B) were mixed in the ratio 3: 1 by volume. The mixed resin was applied on non-stick paper with a brush roller. Carbon Tow sheet was set on the resin coated non-stick paper and the paper attached on tow sheet was removed. The resin was reapplied on that side in which the paper was removed. The resin was impregnated into the fiber-bundle of Tow sheet by using a rubber plate. Another piece of non-stick paper was applied to resin recoated on another side of carbon tow sheet. The specimens were allowed to cure for 5-6 hours. Then, the carbon tow sheet was cut into test pieces measuring 0.5× 15 inches parallel to the fiber direction. The pieces of carbon tow sheet were further cured at room temperature for 1 week. FRP tabs were bonded to the pieces with pliogrip after removing the non-stick paper.

CFRP strips extracted from aged beams

Carbon fiber sheet was removed from bottom surface of beams after three-point bending test was done. Visual inspection was used to select parts of carbon fiber sheet without degradation. After inspection, carbon fiber sheet was cut down to small pieces measuring 0.5×15 inches parallel to the fiber direction. Small FRP tabs were attached at both ends of carbon fiber strips using pliogrip. Tension tests were conducted after grip attachment.

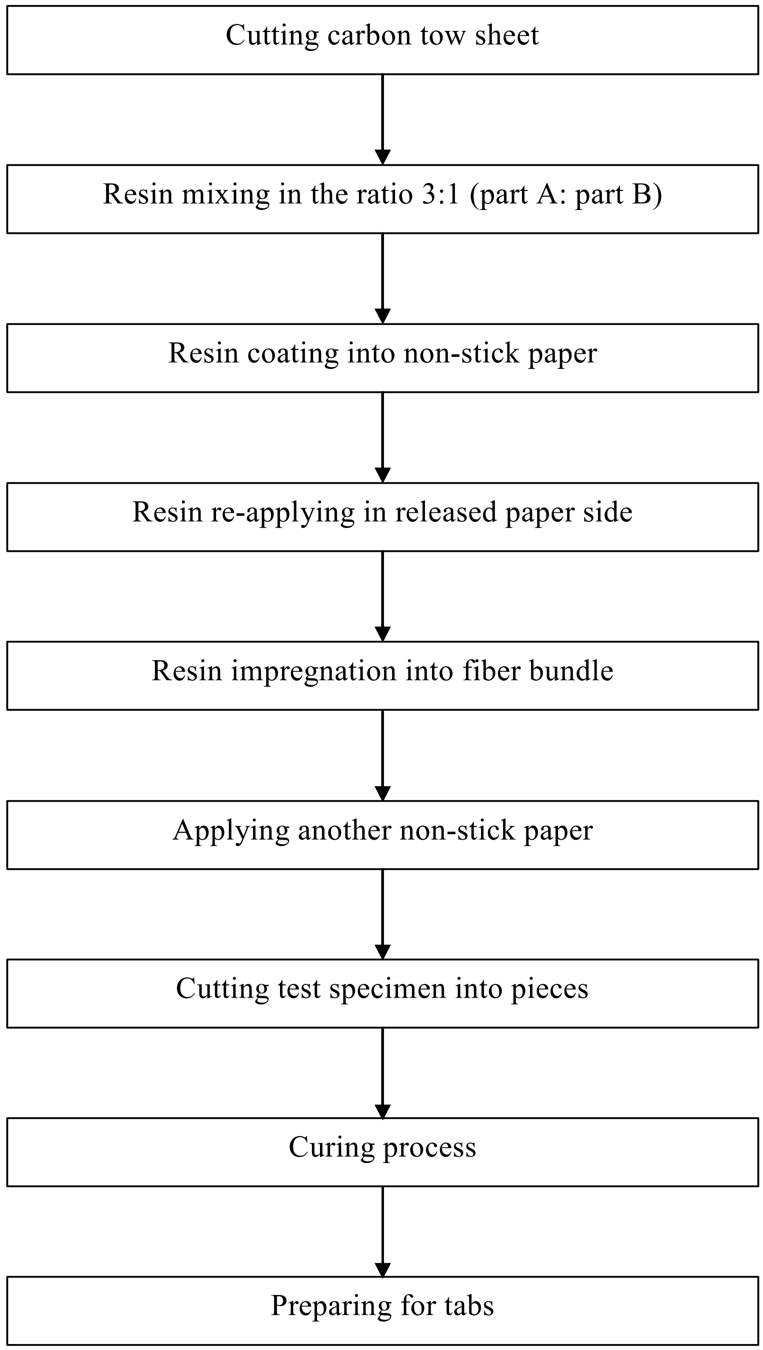

Fig 4.1 Coupon specimens making procedure

Fig 4.2 Carbon fiber strip specimens

4.3 TEST SET-UP AND INSTRUMENTATION

4.3. 1 Three-point loading of beams under accelerated aging

After aging process, the beams were prepared for three point loading test. The top and bottom surfaces of test beams to be bonded with strain gages were sanded and cleaned for smoothness. Concrete strain gages were attached on to the top compression surface of beams while regular strain gages were bonded under the bottom tension surface on carbon fiber wraps. The beams were placed on simple supports such that overhang on each side was at 5 inches. Hydraulic jack was positioned at mid span. The load and deflections of the beams were measured by calibrated load cell and LVDT located at mid span under the beams. Load cell, strain gages and LVDT were connected to data acquisition system for automatic recording.

During testing, loads were slowly applied by a manually controlled system. Beams were loaded and unloaded in several cycles until beam failure. Most of the test beams were loaded and released in 3 cycles until a test beam failed in the last cycle. In each cycle of loading, load was increased higher than the previous cycle loading. In addition, crack widths were measured during loading, before the beam failure.

Fig 4.3 Three-point bending test set-up

4.3.2 Test on tension strips extracted from beams under accelerated aging

CFRP strips were cured for twenty-four hours after grips were attached at both ends. CFRP strip specimens were prepared for attaching a strain gage at mid height of specimens. The strain gage and load cell were connected to the data acquisition system. Load was gradually applied to specimens using Baldwin machine until specimen failure.

Fig 4.4 Carbon fiber strips test-set up

4. 3. 3 Three-point loading of beams under natural aging

Three concrete beams measuring 5”×6”×96”were prepared for three point loading test. The top and bottom surfaces of the test beams to be bonded with strain gages were sanded and cleaned for smoothness. Concrete strain gages were attached on the top compression surfaces of beams, while regular strain gages were bonded under the bottom tension surface on carbon fiber wraps. The beams were placed on simple supports such that overhang on each side was at 6 inches. Hydraulic jack was positioned at mid span. The load and deflections of the beams were measured by celebrated load cell and LVDT located at mid span under the beams. Load cell, strain gages and LVDT were connected to data acquisition system for automatic recording.

4.3. 4 Test on tension strips extracted from beams aged under constant 68 °F

CFRP strips extracted from beams under natural aging at constant 68°F of room temperature were also prepared and set-up in the same way as CFRP strips extracted from beams under accelerated aging in section 4.3.2

4.3.5 Four-point loading of beams under natural aging

The beams measuring 6"×15"×120"were prepared for four point loading test. The top and bottom surface portion of beams were sanded and cleaned until smooth for attaching strain gages. The beams were placed on simple supports having a span of 108 inches. Hydraulic jack positioned at mid span was connected to a load cell placed on a small distribution I –beam. Distribution I–beam rested on two roller and plate supports that were spaced three feet apart on top of the test beam. Load cell and LVDT were calibrated prior to the test to measure the load versus mid-span deflections. The data acquisition system was set to record data at every one second. Loads were slowly applied by manual control. Beams were loaded and unloaded in three cycles with maximum load of 8000 lbs. After third cycle of loading and unloading, beams were naturally aged outside and periodically tested for stiffness loss at the end of first, second and third year, respectively. During each year of natural aging, the beams were subjected to freezing and thawing during winter (snow) season, high and low temperature variation during summer, and temperature variation coupled with humidity variation during rainy season. After aging period, the beams were brought back into the laboratory and new strain gages were attached and the four point loading tests were performed by loading them to 8000 lbs. Again mid-span deflection and strain readings on FRP wraps were recorded. At the end of 3 rd year, beams were tested to failure.

Fig 4.5 Four –point loading test set-up for natural aging beams

4. 3. 6 Test on tension strips extracted from beams under natural weathering

CFRP strips extracted from beams aged under natural weathering for 3 years were prepared and tested in the same way as CFRP strips extracted from beams under accelerated aging in section 4.3.2.

Test results, analyses and discussion are presented in chapter 5.

Chapter 5

CONCRETE BEAM WRAPPED WITH CARBON SHEETS UNDER ACCELERATED AGING

5. 1 INTRODUCTION

The results of bending tests conducted on carbon fiber wrapped beams and tension test on carbon fiber strips are provided in this chapter in forms of graphs and tables. Results from this research are presented in terms of strength, stiffness, and serviceability (for beams only) under different accelerated aging conditions.

Following tests were conducted and the results are elaborated accordingly under different sections.

5.1.1 Water immersion aging at room and elevated temperatures

Three-point bending tests were conducted for wrapped beams aged in water at room and elevated temperatures (110°F and 140°F temperature). CFRP strips were extracted from carbon fabrics of aged beams after conducting beam-bending tests.

5.1.2 Alkaline and salt solution aging at room temperature

Three-point bending tests were conducted on wrapped beams aged in alkaline (pH $\cong$ 13) and salt (pH $\cong$ 7) solutions at room temperature for 3 months. CFRP strips for tension tests were extracted from aged beams after conducting beam-bending tests.

5.1.3 Alkaline and salt solution aging under freeze-thaw conditioning

Three-point bending tests were conducted on wrapped beams aged in alkaline (pH $\cong$ 13) and salt (pH $\cong$ 7) solutions under freeze-thaw conditioning for 6 months. CFRP strips for tension tests were extracted from carbon fabrics of aged beams after conducting beam-bending tests.

5.2 OVERVIEW OF TEST RESULTS

Results of beam bending tests after accelerated aging are analyzed and discussed in terms of ultimate load (moment) capacity, maximum load (experimental/theoretical) ratio, deflection at mid span, crack width and deformability factor [for definition refer to 5.3.4].

Results of CFRP strip specimens are compared as a percent of original (un-aged) strength and stiffness values.

Test results and analysis are presented in the format described below under respective sections of this chapter.

5.3 Results and analysis of beams aged in water at room and elevated temperatures

5.3.1 Load (moment) capacity

5.3.2 Deflection and crack width up to 2 kip load (**Note**: the beams were loaded to 2 kips prior to and after wrapping to establish base values).

5.3.3 Deflection and crack width up to failure load.

5.3.4 Deformability factor.

5.4 Results and analysis of CFRP strips extracted from beams aged in water at room and elevated temperatures

5.4.1 Tensile strength and stiffness of CFRP strips

5.5 Results and analysis of beams aged in alkaline and salt solution at room temperature

5.5.1 Load (moment) capacity

5.5.2 Deflection

5.5.3 Deformability factor

5.6 Results and analysis of CFRP strips extracted from beams aged in salt and alkaline solution at room temperature

5.6.1 Tensile strength and stiffness of CFRP strips

5.7 Results and analysis of beams aged in alkaline and salt solutions under freeze-thaw conditioning

5.7.1 Load (moment) capacity

5.7.2 Deflection

5.7.3 Deformability factor

5.8 Results and analysis of CFRP strips extracted beams aged in salt and alkaline solutions under freeze-thaw conditioning

5.8.1 Tensile strength and stiffness of CFRP strips

5.9 Results and analysis of wrapped and non-wrapped beams

5.3 RESULTS AND ANALYSIS OF BEAMS AGED IN WATER AT ROOM AND ELEVATED TEMPERATURES.

Results from carbon wrapped beams of 5”× 8”×60”aged in water at room, 110 °F and 140 °F temperature at 3, 6, 9 month intervals are presented in terms of maximum failure load, maximum moment, maximum deflection (recorded) and maximum crack width (recorded) in Tables 5-1 to 5-3.

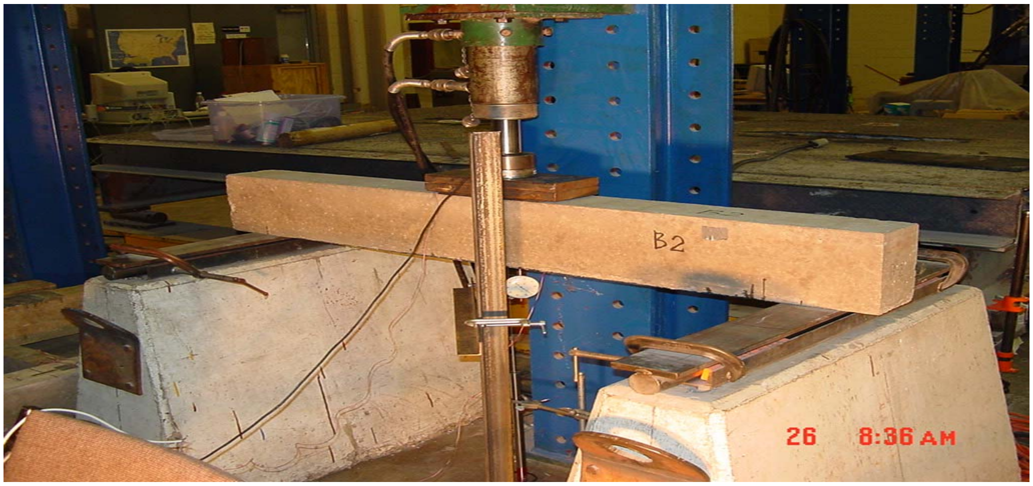

Fig 5.1 Three-point bending test of beam aged in water (3 months)

Table 5-1 Three-point bending test results for beams aged in water (3 months)

Age (month)	Temp (F)	Beam	Wrap* Type	Max load (recorded) (kips)	Max. Moment (recorded) (kip-ft)	Max deflection (recorded) (in)	Max crack-width (recorded) (in)
3	room	B3	b	10.89	11.35	0.507	0.021
	110	E11	b	10.75	11.20	0.500	0.028
	140	A4	b	10.560	11.00	0.467	0.04
		A5	b	10.61	11.06	0.281	0.025

Note: *b: one longitudinal layer of carbon fiber wrap at the beam bottom (full length)
Test span for three-point bending = 50 inch
Max deflection and crack width (recorded) correspond to values between 70 to 100 % of maximum load and varied in each beam test.

Table 5-2 Three-point bending test results for beams aged in water (6 months)

Age (month)	Temp (F)	Beam	Wrap* Type	Max load (recorded) (kips)	Max. Moment (recorded) (kip-ft)	Max deflection (recorded) (in)	Max crack-width (recorded) (in)
6	room	B1	b	11.52	12.00	0.459	0.027
		B2	b	tested up to 2 kips and placed in the tanks for further condition			
	110	E3	b	11.01	11.47	0.348	0.03
		E4	b	10.61	11.09	0.342	0.02
	140	D2	b	tested up to 2 kips and placed in the tanks for further condition			
		D5	b	10.82	11.04	0.349	0.025

Note: *b: one longitudinal layer of carbon fiber wrap at the beam bottom (full length)
Test span for three-point bending = 50 inch
Max deflection and crack width (recorded) correspond to values between 70 to 100 % of maximum load and varied in each beam test.

Table 5-3 Three-point bending test results for beams aged in water (9 months)

Age (month)	Temp (F)	Beam	Wrap* Type	Max load (recorded) (kips)	Max. Moment (recorded) (kip-ft)	Max deflection (recorded) (in)	Max crack-width (recorded) (in)
9	Room	B2	b	12.27	12.78	0.407	0.025
		B4	b	11.43	11.91	0.436	0.032
		B5	b	12.79	13.33	0.412	0.03
	110	E1	b	12.76	13.29	0.427	0.025
		E2	b	10.36	10.79	0.360	0.02
	140	D1	b	11.84	12.33	0.357	0.023
		D2	b	10.82	11.27	0.444	0.025
		D4	b	10.29	10.71	0.520	0.028

Note: *b: one longitudinal layer of carbon fiber wrap at the beam bottom (full length)
Test span for three-point bending = 50 inch
Max deflection and crack width (recorded) correspond to values between 70 to 100 % of maximum load and varied in each beam test.

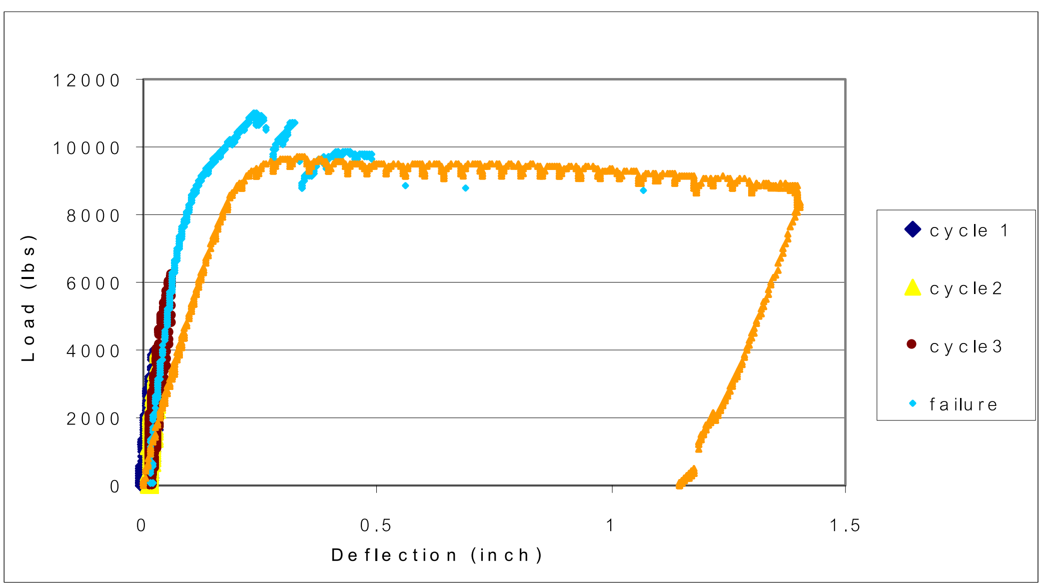

Fig 5.2 Load-deflection curve of beams aged in water (110°F, 6 months)

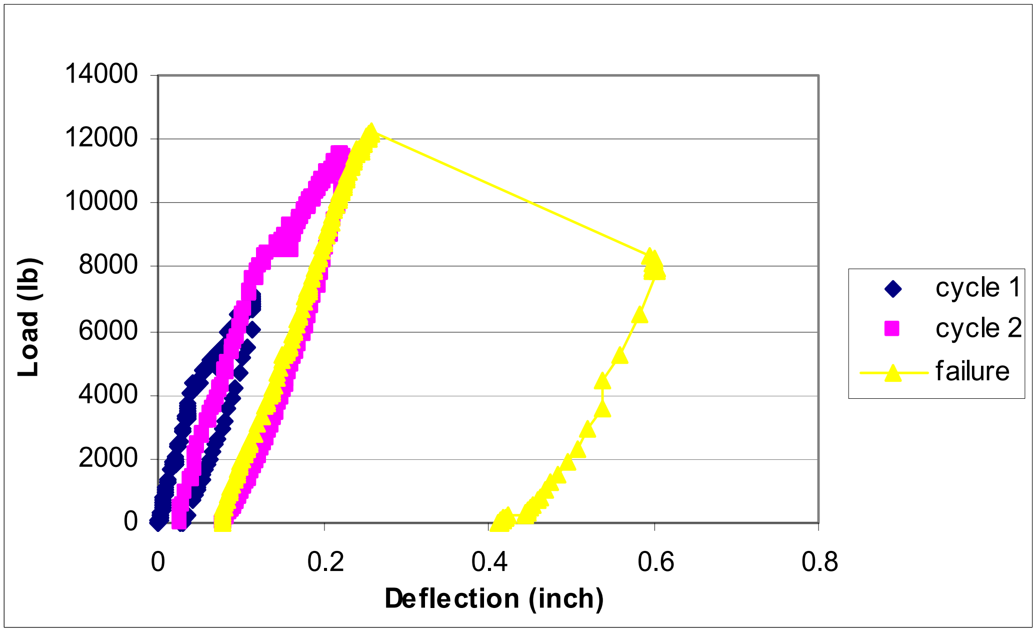

Fig 5.3 Load-deflection curve of beams aged in water (room temperature for 9 months)

5.3.1 Load (moment) capacity

Experimental bending moment values of beams under three-point bending are compared with theoretical values based on bending theory for reinforced concrete beams. In addition, ratio of experimental versus theoretical values of loads (moments) were calculated for comparison purposes. Theoretical computations of moment capacity are presented in chapter 8.

The maximum experimental to theoretical load (moment) ratios of wrapped beams under elevated temperature aging are shown in Tables 5-4 to 5-6. Average ratio of experimental to theoretical load (moment) capacity exceeded 1 for all wrapped concrete beams aged for 3, 6 and 9 months in water at elevated temperatures. Average experimental to theoretical load (moment) ratios indicate a trend of reduction in load (moment) capacity with increasing temperatures. However, a clear trend of load (moment) capacity reduction with a combination of temperature and aging duration was not observed.

Table 5-4 Maximum (Exptl./Theor) load (moment) ratios for wrapped beams aged in water (3 months)

Temp (F)	Beam	Age (months)	Wrap* Type	Max load (Exptl.) (kips)	Max moment (Exptl.) (kip-ft)	Max load (Theor.) (kips)	Max moment (Theor.) (kip-ft)	Max load ratio (Exptl./Theor)	Avg Max load ratio (Exptl./Theor)
room	B3	3	b	10.89	11.35	10.32	10.75	1.055	1.055
110	E11	3	b	10.75	11.20	10.32	10.75	1.042	1.042
140	A4	3	b	10.56	11.00	10.32	10.75	1.023	1.026
	A5	3	b	10.61	11.06	10.32	10.75	1.028	

Note: *b**:** one longitudinal layer of carbon fiber wrap at the beam bottom (full length)
Test span for three-point bending = 50 inch
Beam dimension: 5” ×8” × 60”

Table 5-5 Maximum (Exptl./Theor) load (moment) ratios for wrapped beams aged in water (6 months)

Temp (F)	Beam	Age (months)	Wrap* Type	Max load (Exptl.) (kips)	Max moment (Exptl.) (kip-ft)	Max load (Theor.) (kips)	Max moment (Theor.) (kip-ft)	Max load ratio (Exptl./Theor)	Avg Max load ratio (Exptl./Theor))
room	B1	6	b	11.52	12.00	10.32	10.75	1.116	1.116
110	E3	6	b	11.01	11.47	10.32	10.75	1.067	1.050
	E4	6	b	10.65	11.09	10.32	10.75	1.032	
140	D5	6	b	10.60	11.04	10.32	10.75	1.026	1.026

Note: *b: one longitudinal layer of carbon fiber wrap at the beam bottom (full length)
Test span for three-point bending = 50 inch
Beam dimension: 5” ×8” × 60”

Table 5-6 Maximum (Exptl./Theor) load (moment) ratios for wrapped beams aged in water (9 months)

Temp (F)	Beam	Age (months)	Wrap* Type	Max load (Exptl.) (kips)	Max moment (Exptl.) (kip-ft)	Max load (Theor.) (kips)	Max moment (Theor.) (kip-ft)	Max load ratio (Exptl./Theor)	Avg Max load ratio (Exptl./Theor))
room	B2	9	b	12.27	12.78	10.32	10.75	1.189	1.178
	B4	9	b	11.43	11.91	10.32	10.75	1.107	
	B5	9	b	12.79	13.33	10.32	10.75	1.239	
110	E1	9	b	12.76	13.29	10.32	10.75	1.236	1.120
	E2	9	b	10.36	10.79	10.32	10.75	1.004	
140	D1	9	b	11.84	12.33	10.32	10.75	1.147	1.064
	D2	9	b	10.82	11.27	10.32	10.75	1.048	
	D4	9	b	10.29	10.73	10.32	10.75	0.998	

Note: *b: one longitudinal layer of carbon fiber wrap at the beam bottom (full length)
Test span for three-point bending = 50 inch
Beam dimension: 5” ×8” × 60”

5.3.2 Deflection and crack width up to 2 kip load

The deflection and crack width versus aging duration at 2 kip load for wrapped beams aged in water at elevated temperatures are presented in Figures 5.4 and 5.5. Deflection at 2 kip load level gradually increased with aging duration. The increase in deflection is higher and more evident at 140°F as compared to room and 110°F aging for 2 kip load (Figure 5.4) .The crack width of wrapped beams aged in water at room, 110°F and 140°F increased with aging duration (Figure 5.5).

Table 5-7 Crack width of wrapped beams aged in water (2 kip load)

Temperature (°F)	*Crack width of wrapped beams aged in water at 2 kips (in)		
	3 months	**6 months**	**9 months**
room	0.001667	0.002	0.002
110	0.002	0.002	0.00233
140	0.001833	0.00233	0.00256

***Note**: Values are interpolated from graph

Table 5-8 Crack width increase in wrapped beams aged in water (2 kip load)

Temperature (°F)	Increase in crack width at 2 kips (%)		
	3 months	**6 months**	**9 months**
room	0	0	0
110	19.97	0	16.5
140	9.96	16.5	28

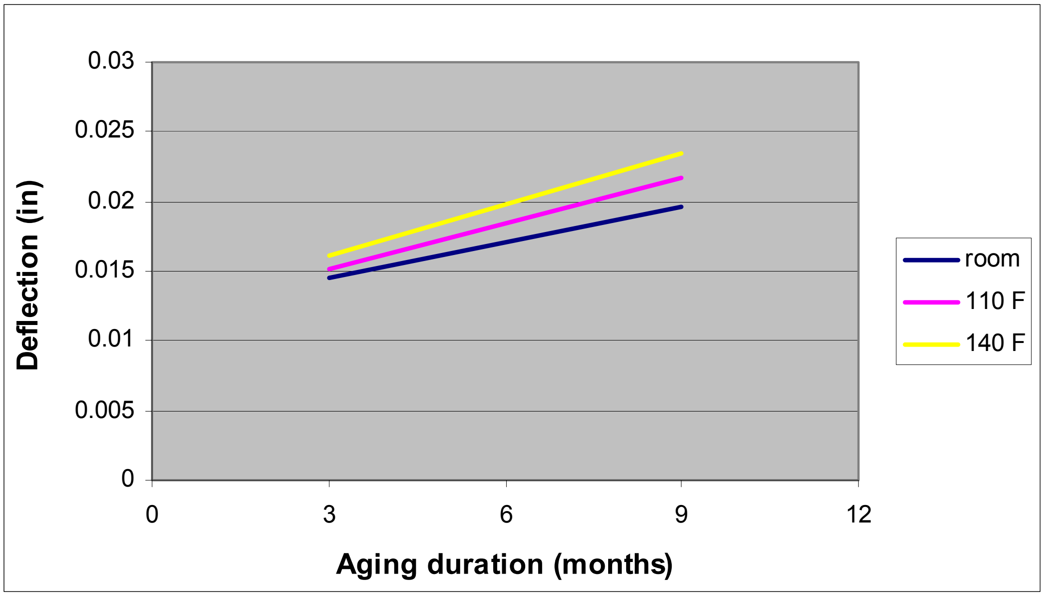

Fig 5.4 Deflection of wrapped beams aged in water at 2 kip load

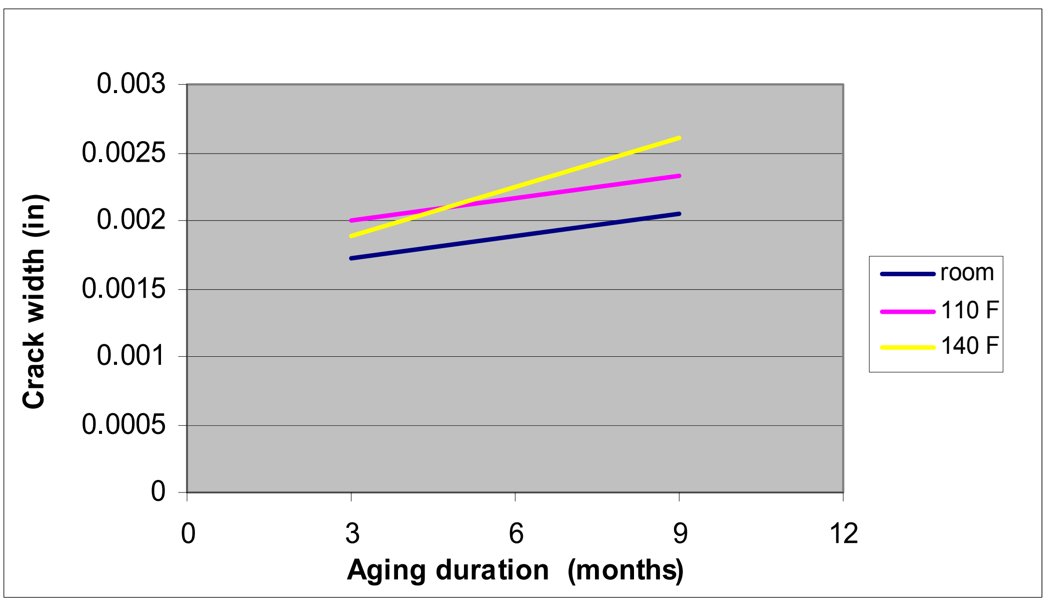

Fig 5.5 Crack widths of wrapped beams aged in water at 2 kip load

5.3.3 Deflection and Crack width up to failure load

Deflection values of each beam for different serviceability deflection limits specified by ACI 318-02 are obtained from experimental results and compared in Table 5.9.

Table 5-9 Loads at different limiting deflection values of wrapped beams in water aging

Temp (F)	Beam	Age (months)	Wrap* Type	Load at standard deflection limit (kips)		
				l/360 (0.1667 in)	l/240 (0.250 in)	l/180 (0.333in)
room	B3	3	b	7.76	8.88	10.31
110	E11		b	7.74	8.53	9.45
140	A4		b	7.48	8.94	9.01
	A5		b	7.74	9.48	-
room	B1	6	b	8.12	9.02	9.89
110			b	7.64	8.65	9.54
	E4		b	7.01	-	-
140	D5		b	7.52	7.97	9.21
room	B2	9	b	7.55	9.43	-
	B4		b	8.44	9.09	10.87
	B5		b	8.42	10.03	11.22
110	E1		b	7.87	9.76	11.03
	E2		b	7.53	8.46	-
140	D1		b	8.70	10.06	11.10
	D2		b	6.22	8.12	9.67
	D4		b	4.45	5.97	6.96

***Note** b: one longitudinal layer of carbon fiber wrap at the beam bottom (full length)
l = span
Test span for three-point bending = 50 inch
Beam dimension: 5” ×8” × 60”

The ratios of load at each deflection limit (l/360, l/240 and l/180) to maximum experimental load for each beam aged in water are presented in Table 5.10.

The ratios of load at each deflection limit (l/360, l/240 and l/180) to maximum load of beams aged for 3, 6 and 9 months in water decreased directly with aging duration (Figures 5.6 to 5.8) and temperature (Figures 5.9 to 5.11).

Table 5-10 Average ratio of load at serviceability deflection to maximum load

Temp (°F)	Avg. ratio of load at deflection (span/360) to Max load			Avg. ratio of load at deflection (span/240) to Max load			Avg. ratio of load at deflection (span/180) to Max load		
	Aging duration (months)			Aging duration (months)			Aging duration (months)		
	3	6	9	3	6	9	3	6	9
room	0.712	0.706	0.677	0.815	0.784	0.782	0.946	0.867	0.877
110F	0.720	0.694	0.672	0.793	0.786	0.774	0.880	0.867	0.864
140F	0.718	0.709	0.663	0.770	0.752	0.735	0.879	0.865	0.846

The ratios of load at each deflection limit (l/360, l/240 and l/180) to maximum load of beams aged for 3, 6 and 9 months in water aging decreased with temperature and aging duration.

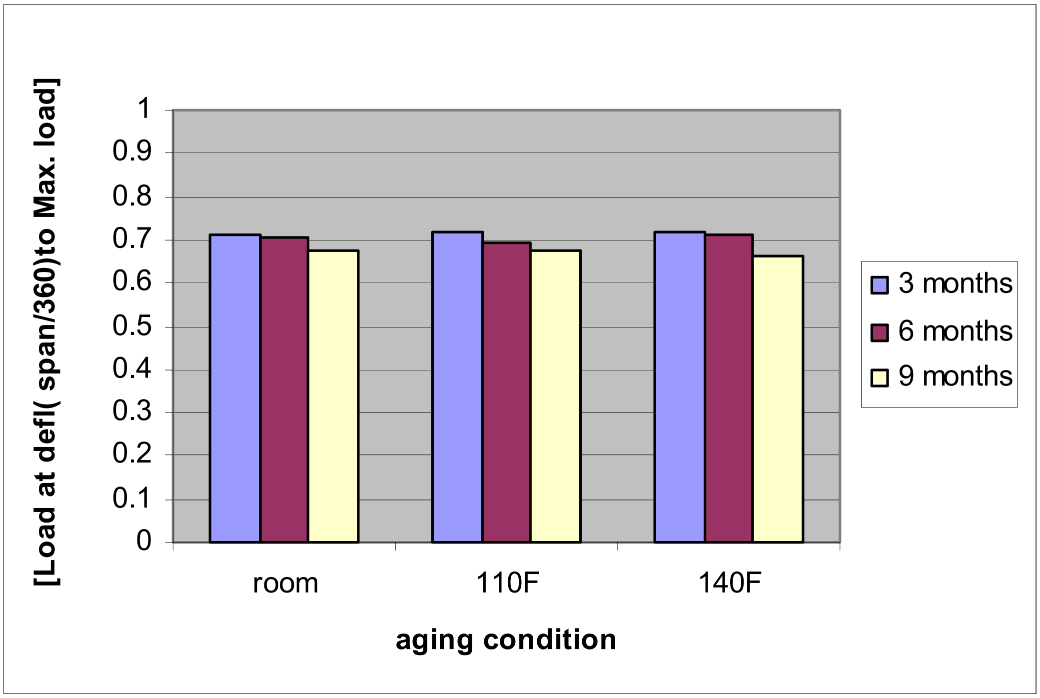

Fig 5.6 Avg. ratio of load at deflection (span/360) to max load under different aging conditions

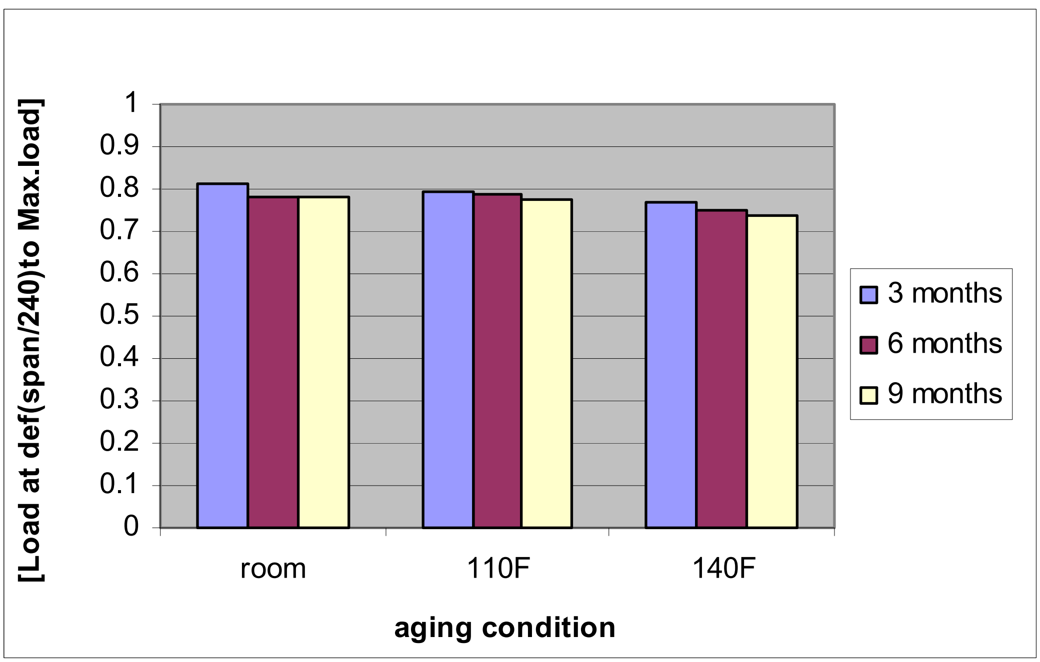

Fig 5.7 Avg. ratio of load at deflection (span/240) to max load under different aging conditions

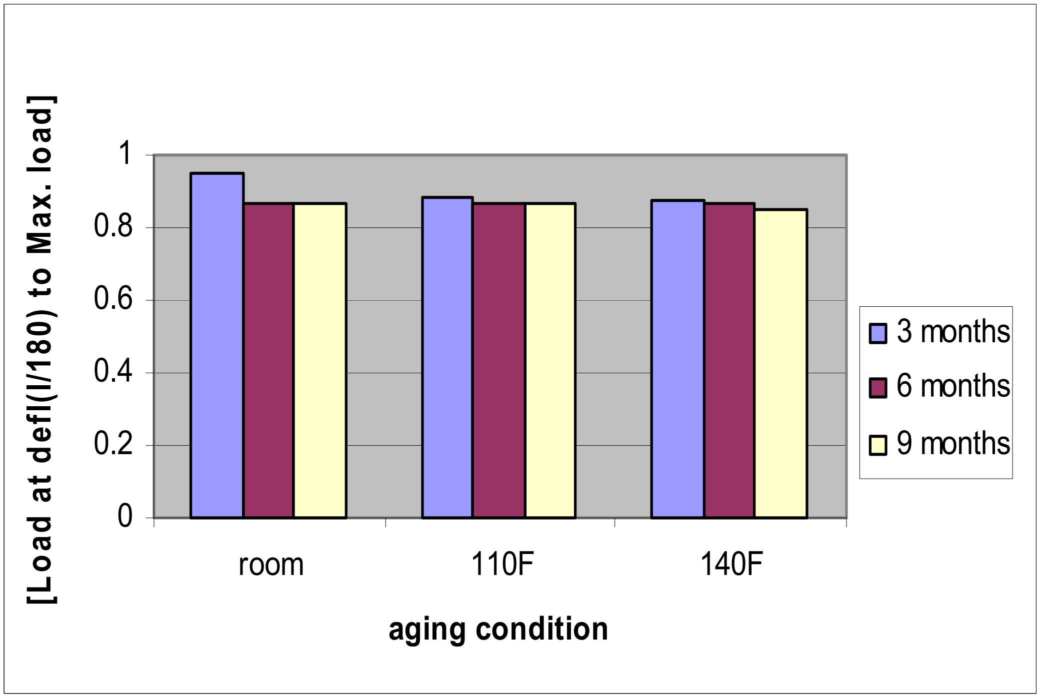

Fig 5.8 Avg. ratio of load at deflection (span/180) to max load under different aging conditions

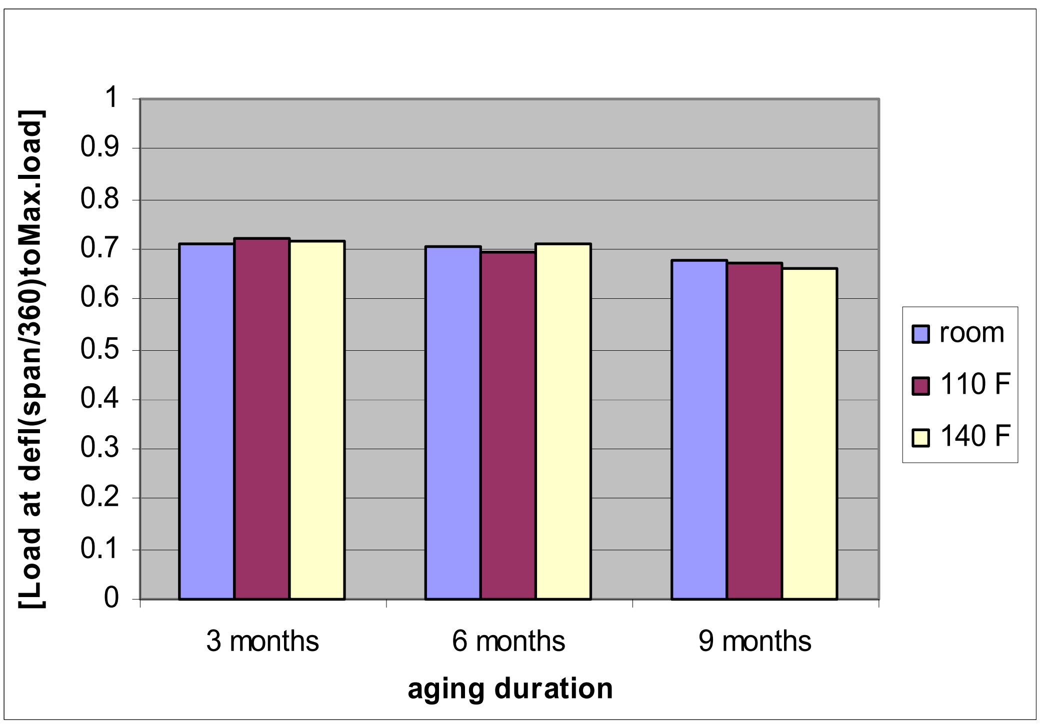

Fig 5.9 Avg. ratio of load at deflection (span/360) to max load under different aging durations

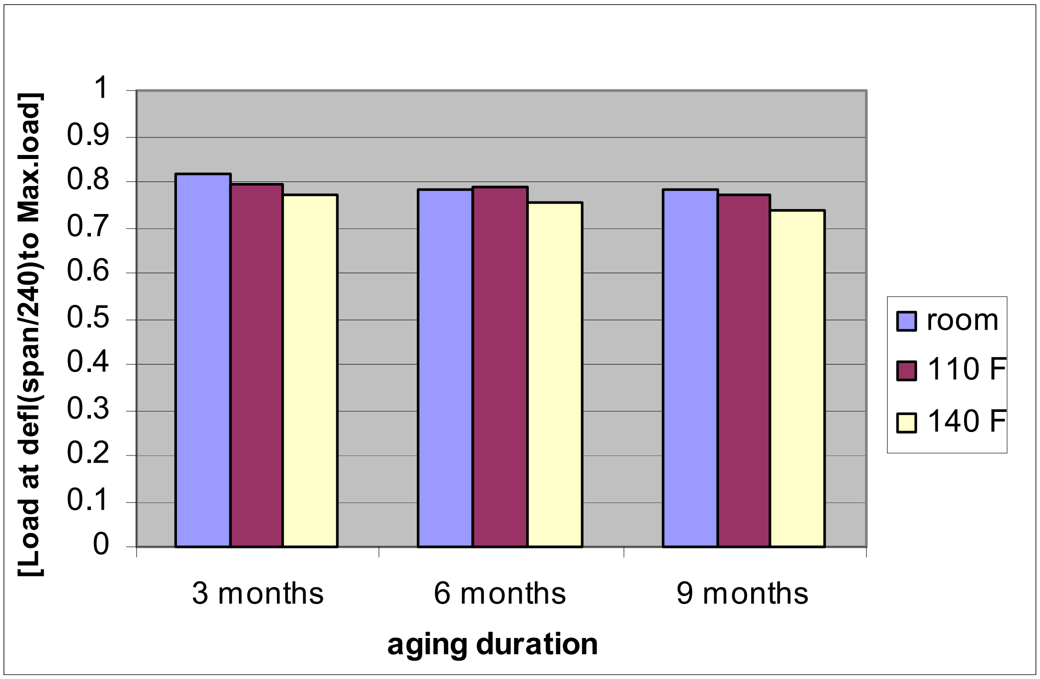

Fig 5.10 Avg. ratio of load at deflection (span/240) to max load under different aging durations

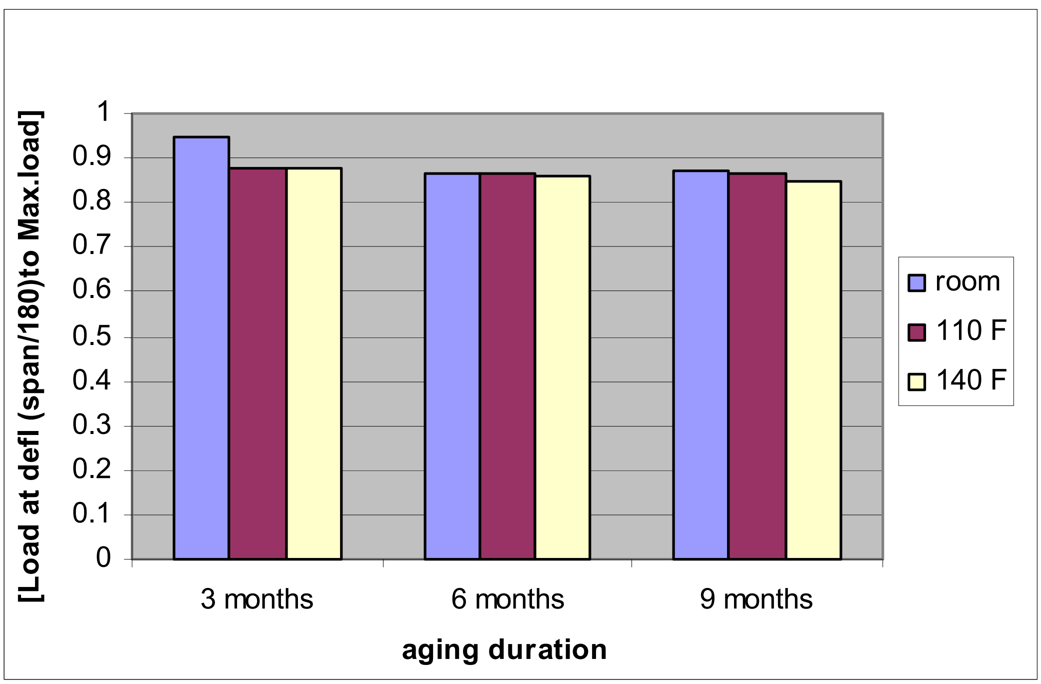

Fig 5.11 Avg. ratio of load at deflection (span/180) to max load under different aging durations

Compared to room temperature values, maximum reduction in the ratio of load at limiting deflection (l/360, l/240 and l/180) to maximum load at 110 °F and 140 °F was 6.97 % and 7.08%, respectively during the 9 months aging as shown in Table 5-11.

Table 5-11 Comparison of average ratios of load at deflection limit to max load with respect to room temperature values

Temp (°F)	% reduction of load at limiting deflection l/360ratio to max load ratio with respect to room temperature values			% reduction of load at limiting deflection l/240ratio to max load ratio with respect to room temperature values			% reduction of load at limiting deflection l/180 ratio to max load ratio with respect to room temperature values		
	months			months			months		
	3	6	9	3	6	9	3	6	9
110F	0	1.70	0.739	2.69	0	1.02	6.97	0	0.690
140F	0	0	2.07	4.66	4.08	6.01	7.08	0.23	2.75

Compared to values at 3 months, maximum reduction in the ratio of load at limiting deflection (l/360, l/240 and l/180) to maximum load for all the temperature variation (room, 110 °F and 140 °F) was under 7.29 % as shown in Table 5-12.

Table 5-12 Comparison of average ratios of load at deflection limit to max load with respect to 3 month values

Temp (°F)	% reduction of load at limiting deflection l/360ratio to max load ratio with respect to 3 month values		% reduction of load at limiting deflection l/240ratio to max load ratio with respect to 3 month values		% reduction of load at limiting deflection l/180ratio to max load ratio with respect to 3 month values	
	months		months		months	
	6	**9**	**6**	**9**	**6**	**9**
room	0	0	2.70	5.52	6.97	7.29
110F	1.70	0	0.255	4.08	0	0
140F	0.739	2.07	1.023	6.10	0.680	2.75

Maximum reduction in the ratio of load at limiting deflection (l/360, l/240 and l/180) to maximum load for water aging at room, 110 ^{0}F and 140 ^{0}F during 9 months was 7.29%, when compared to either room temperature or 3 month values.

Loads at limiting crack width (0.016 in) decreased directly with increase of temperature and duration of aging as shown in Table 5-13

Table 5-13 Load at crack width limit (0.016 in) of beams aged in water

Temp (F)	Beam	Age (months)	Wrap* Type	Load at limiting crack width(0.016 in) (kips)	Load at limiting crack width (0.016in) to max load
room	B3	3	b	8.00	0.734
110	E11		b	7.50	0.697
140	A4		b	7.20	0.682
	A5		b	7.20	0.678
room	B1	6	b	8.32	0.722
110	E3		b	7.50	0.681
	E4		b	7.50	0.707
140	D5		b	7.33	0.678
room	B2	9	b	9.00	0.734
	B4		b	8.20	0.717
	B5		b	7.80	0.610
110	E1		b	8.44	0.622
	E2		b	7.00	0.676
140	D1		b	7.50	0.633
	D2		b	7.30	0.678
	D4		b	7.00	0.681

Note: *b: one longitudinal layer of carbon fiber wrap at the beam bottom (full length)
Test span for three-point bending = 50 inch
Beam dimension: 5” ×8” × 60”

The ratios of load at limiting crack width (0.016 in) to maximum load of beams aged in water are presented in Table 5.14.

The ratios of load at limiting crack width (0.016 in) to maximum load of beams aged in water decreased clearly with increases in temperature and aging duration as shown in Figures 5.12 and 5.13.

Table 5-14 Ratio of load at limiting crack width (0.016 in) to maximum load in water

Temp (°F)	Avg. ratio of load at limiting crack width (0.016 in) to Max load		
	Aging duration (months)		
	3	6	9
room	0.739	0.722	0.687
110F	0.697	0.694	0.669
140F	0.680	0.678	0.664

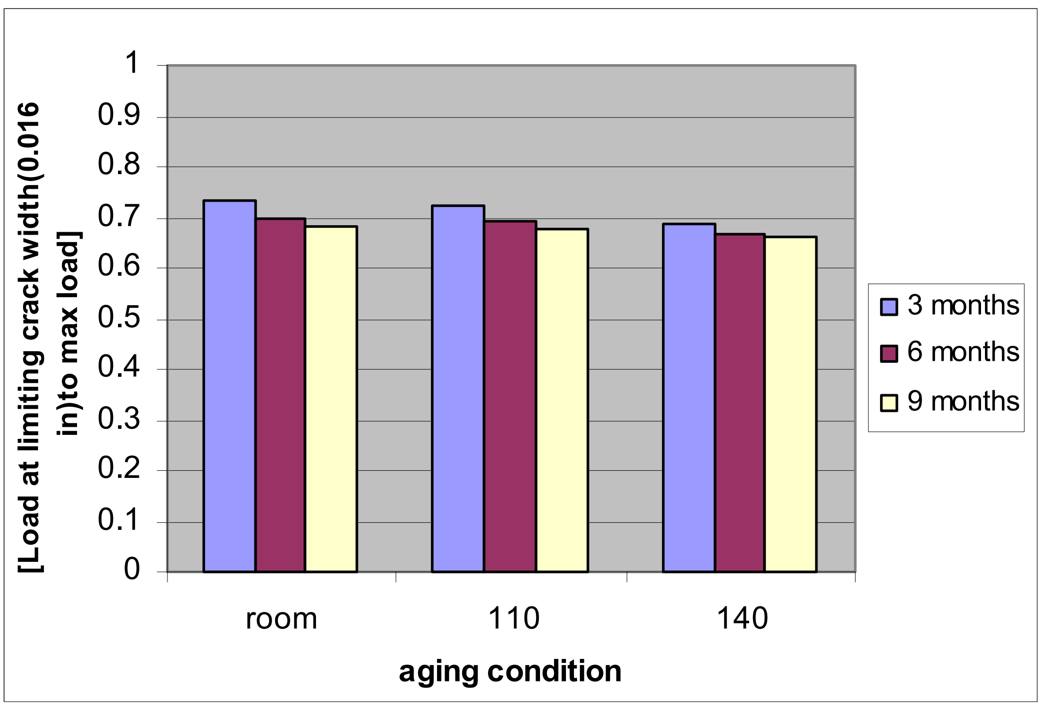

Fig 5.12 Avg. ratio of load at limiting crack width (0.016) to max load under different aging conditions

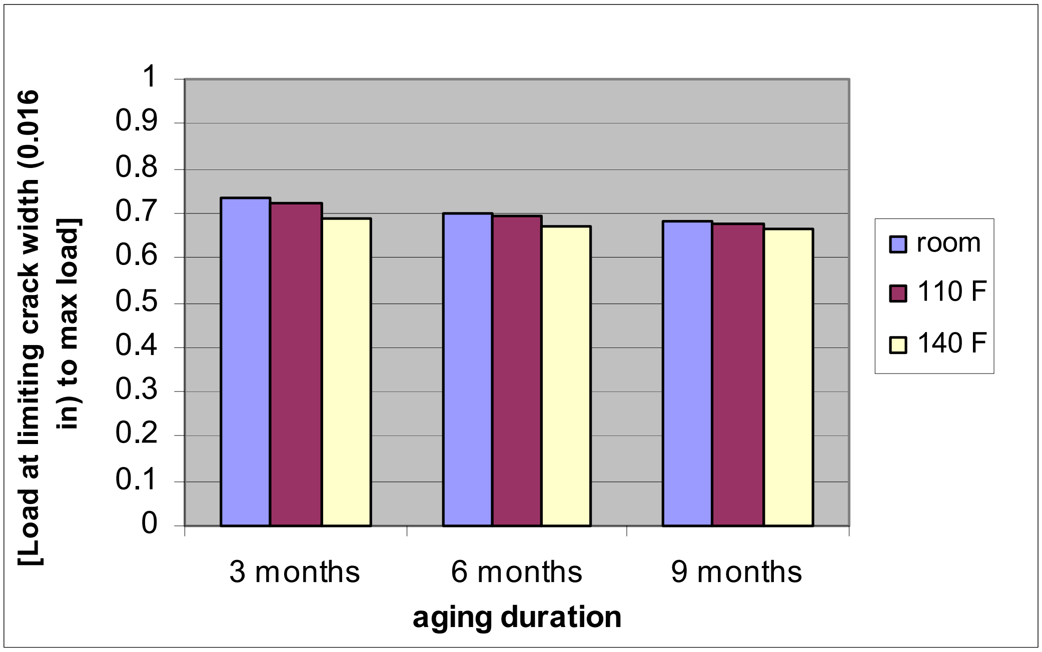

Fig 5.13 Avg. ratio of load at limiting crack width (0.016) to max load under different aging durations

Compared to room temperature values, maximum reduction in the ratio of load at limiting crack width (0.016 in) to maximum load at 110°F and 140°F was 5.68% and 6.09%, respectively, during 9 months of aging duration as shown in Table 5-15.

Table 5-15 Reduction in the ratio of load at limiting crack width (0.016) to Max load compared to room temperature

Temp (°F)	Reduction of load at limiting crack width (0.016) to max load compared to load ratio at room temperature (%)		
	Aging duration (months)		
	3	6	9
110°F	5.68	3.88	2.62
140°F	7.98	6.09	3.35

Compared to values at 3 months, maximum reduction in the ratio of load at limiting crack width (0.016 in) to maximum load for all the temperature variation (room, 110 °F and 140 °F) was under 7.04 % as shown in Table 5-16.

Table 5-16 Reduction in the ratio of load at limiting crack width (0.016) to Max load compared to 3 months

Temp (°F)	Reduction of load at limiting crack width (0.016) to max load compared to load ratio (room, 110°F and 140°F)at 3 months (%)	
	Months	
	6	9
room	2.30	7.04
110°F	0.43	4.02
140°F	0.29	2.35

Maximum reduction in the ratio of load at limiting crack-width (0.016”) to maximum load for water aging at room, 110 ^{0}F and 140 ^{0}F during 9 months was 7.98%, when compared to either room temperature or 3 month values

5.3.4 Deformability factor

Traditionally, energy absorption of steel reinforced concrete beams is indicated by ductility, which is defined as the ratio of deflection (or curvature or rotation) at ultimate to those values at yielding of steel. However, energy absorption of composite reinforced concrete beams is given by deformability factor, which is defined as the ratio of energy absorption (or area under moment curvature or load–deflection curve) at ultimate to energy absorption at limiting curvature value (GangaRao and Vijay, 1998). Limiting value of curvature is based on serviceability criteria of both deflection and crack width (hence, unified), (Vijay and GangaRao, 2001). ACI 318/318R-96 specified deflections and crack-width limits are shown below.

1. The serviceability deflection limit of l/180 (ACI 318/318R-96)
2. The crack-width limit of 0.016 in. (ACI 318/318R-96)

Other serviceability deflection limits such as l/240, l/360 etc. will improve the deformability factor, if deflections are the governing parameters as compared to crack-width. For concrete beams reinforced with GFRP bars, l/180 was found to be a better choice for unifying the two serviceability limit states of deflection and crack-width (Vijay and GangaRao, 2001).

Based on moment-curvature diagrams of over 50 FRP reinforced beams, Vijay and GangaRao (2001) experimentally determined that maximum unified curvature at a service load that satisfied both deflection and crack-width serviceability limits should be limited to (0.005/d) rad./in., where "d" is the effective depth of a concrete beam.

From wrapped beam bending test data, the average deformability factor of wrapped beams aged under water at room, 110°F and 140°F temperatures are:

- 3 months are 14.73, 14.07 and 12.00, respectively
- 6 months are 14.32, 13.74 and 11.72, respectively
- 9 months are 11.93, 11.06 and 10.39, respectively

The average deformability factors decreased directly with increases in temperature and aging duration as shown in Tables 5-17 to 5-20 and Figs 5.14 and 5.15.

Table 5-17 Maximum load/deflection, Maximum (Exptl./Theor) load ratio and deformability factor for wrapped beams aged in water (3 months)

Type	Beam	Age (months)	Wrap* Type	Max load (Exptl.) (kips)	Max def (Exptl.) (in)	Max load ratio (Exptl./Theor.)	Deformability (A_u/A_e)
room	B3	3	b	10.89	0.340	1.055	14.73
110	E11	3	b	10.75	0.500	1.042	14.02
140	A4	3	b	10.56	0.467	1.023	11.39
	A5	3	b	10.61	0.281	1.028	12.60

Note: *b: one longitudinal layer of carbon fiber wrap at the beam bottom (full length)
Test span for three-point bending = 50 in
Beam dimension: 5” ×8” × 60”
$\mathbf{A_u}$ = area under load-deflection curve at ultimate load capacity
$\mathbf{A_e}$ = area under load-deflection curve at serviceability deflection limit of governing minimum value from (l/180) or crack width of 0.016in

Table 5-18 Maximum load/deflection, Maximum (Exptl./Theor) load ratio and deformability factor for wrapped beams aged in water (6months)

Type	Beam	Age (months)	Wrap* Type	Max load (Exptl.) (kips)	Max def (Exptl.) (in)	Max load ratio (Exptl./Theor.)	Deformability (A_u/A_e)
Room	B1	6	b	11.52	0.459	1.116	14.32
110	E3	6	b	11.01	0.328	1.067	13.45
	E4	6	b	10.65	0.342	1.032	14.03
140	D5	6	b	10.60	0.349	1.026	11.72

Note: *b: one longitudinal layer of carbon fiber wrap at the beam bottom (full length)
Test span for three-point bending = 50 in
Beam dimension: 5” ×8” × 60”
$\mathbf{A_u}$ = area under load-deflection curve at ultimate load capacity
$\mathbf{A_e}$ = area under load-deflection curve at serviceability deflection limit of governing minimum value from (l/180) or crack width of 0.016in

Table 5-19 Maximum load/ deflection, Maximum (Exptl./Theor) load ratio and deformability factor for wrapped beams aged in water (9 months)

Type	Beam	Age (months)	Wrap* Type	Max load (Exptl.) (kips)	Max def (Exptl.) (in)	Max load ratio (Exptl. /Theor.)	Deformability (A_u/A_e)
room	B2	9	b	12.27	0.407	1.189	10.93
	B4	9	b	11.43	0.436	1.107	10.29
	B5	9	b	12.79	0.412	1.239	14.56
110	E1	9	b	12.76	0.427	1.236	11.53
	E2	9	b	10.36	0.360	1.004	10.58
140	D1	9	b	11.84	0.357	1.147	11.07
	D2	9	b	10.82	0.444	1.048	10.13
	D4	9	b	10.29	0.520	0.998	10.09

Note: *b: one longitudinal layer of carbon fiber wrap at the beam bottom (full length)

Test span for three-point bending = 50 in

Beam dimension: 5” ×8” × 60”

$\mathbf{A_u}$ = area under load-deflection curve at ultimate load capacity

$\mathbf{A_e}$ = area under load-deflection curve at serviceability deflection limit of governing minimum value from (L/180) or crack width of 0.016in

Table 5-20 Average deformability factors of beams aged in water

Temp (°F)	Average deformability factors		
	Aging duration (months)		
	3	6	9
room	14.73	14.32	11.93
110F	14.07	13.74	11.06
140F	12	11.72	10.39

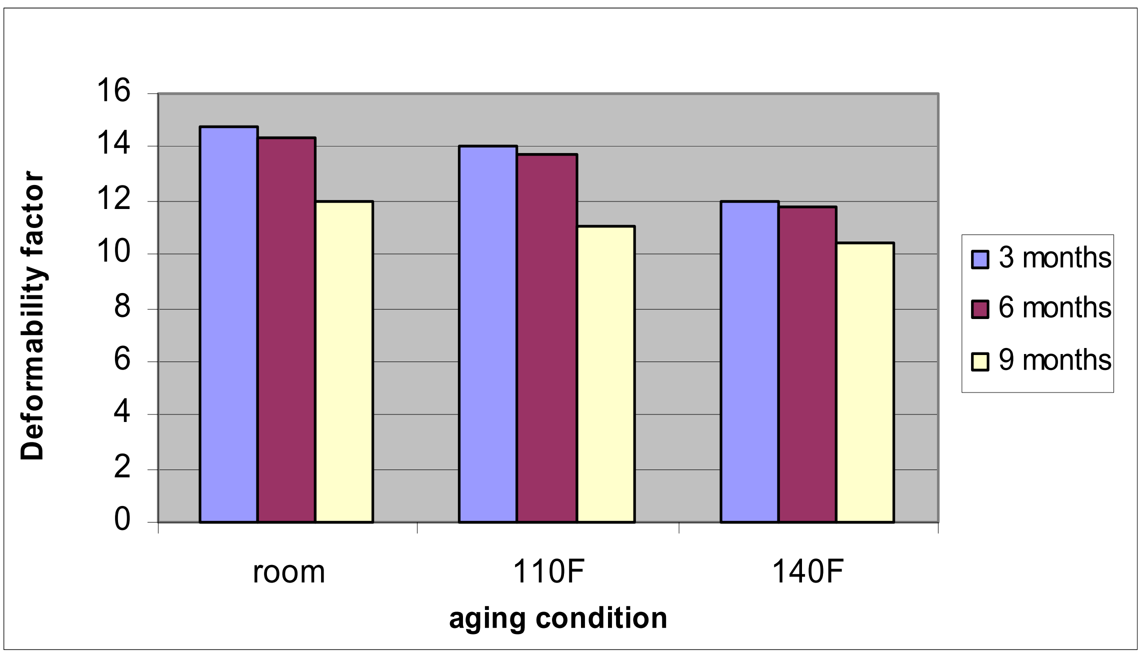

Fig 5.14 Avg. deformability factors of wrapped beams aged in water for different aging conditions

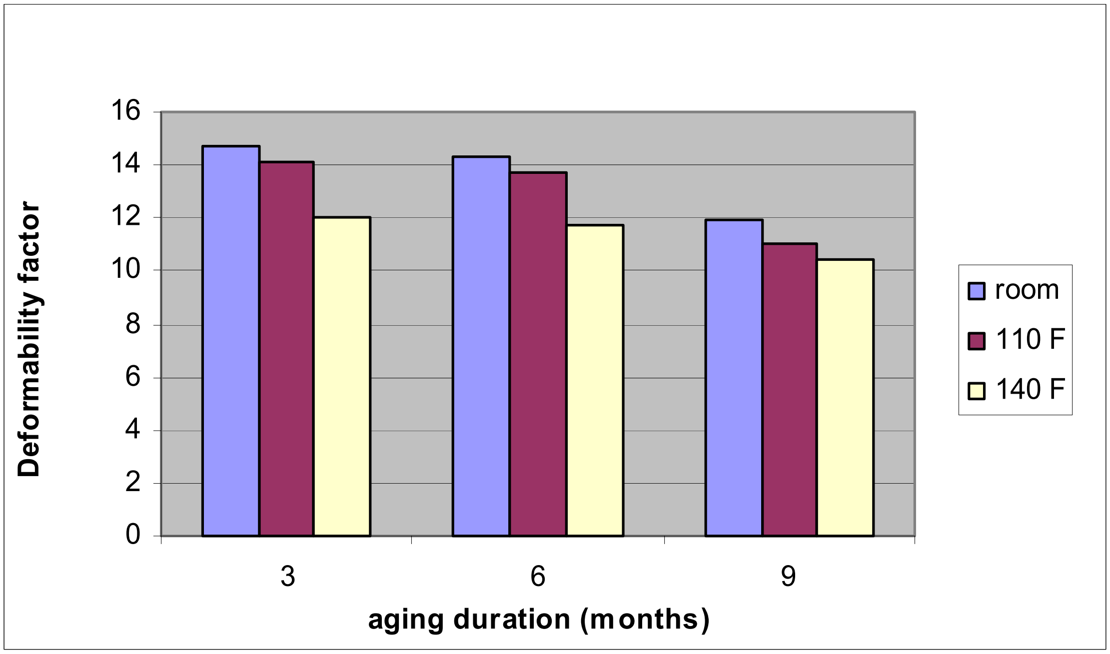

Fig 5.15 Avg. deformability factors of wrapped beams aged in water for different aging durations

Compared to room temperature, reductions in average deformability factor at 110 °F and 140 °F were 7.29 % and 12.91%, respectively during the 9 month aging.

5.4 RESULTS AND ANALYSIS OF CFRP EXTRACTED FROM BEAMS AGED IN WATER AT ROOM AND ELEVATED TEMPERATURES

The carbon fiber sheets were extracted from wrapped beams aged in water (refer to section 5.3) after three-point loading test. The carbon fiber strips used for coupon specimen preparation were selected such that any visible damaged or ruptured sections were avoided. The results in terms of fabric tensile strength and stiffness are presented in Tables 5-21 to 5-24. In addition, tensile strength and stiffness results of aged carbon strips from new fiber carbon sheets are presented in Table 5-25.

Table 5-21 Tension test results of CFRP strips extracted from beams aged in water (3 months)

Age (months)	Temp (°F)	Sample	Maximum load (kips)	Max Load (kips)		Stiffness (Msi)
				Avg.	SD (%)	
3	room	B3/1	1.500	1.550	3.22	31.5
		B3/2	1.550			
		B3/3	1.600			
	110	E11/1	1.400	1.483	7.01	31.4
		E11/2	1.450			
		E11/3	1.600			
	140	A4/1	1.250	1.400	12.86	31.5
		A4/2	1.450			
		A4/3	1.600			
	140	A5/1	1.150	1.383	14.61	31.4
		A5/2	1.500			
		A5/3	1.500			

Note : Sample B3, E11etc. correspond to the beams from which the strips were extracted.

: It should be noted that the tensile load capacity of CFRP strips / unit width (0.5 inch wide) used as a basis for comparison. Stress computation using fiber volume fraction or resin thickness is avoided.

Table 5-22 Tension test results of strips extracted from beams aged in water (6 months)

Age (months)	Temp (F)	Sample	Maximum load (kips)	Max Load (kips)		Stiffness (Msi)
				Avg.	SD (%)	
6	room	B1/1	1.450	1.500	8.8	32.0
		B1/2	1.550			
		B1/3	1.500			
	110	E3/1	1.600	1.433	10.68	31.4
		E3/2	1.300			
		E3/3	1.400			
	110	E4/1	1.540	1.513	13.28	31.2
		E4/2	1.700			
		E5/3	1.300			
	140	D5/1	1.200	1.383	22.9	31.1
		D5/2	1.750			
		D5/3	1.200			

Note : Sample B1, E3etc. correspond to the beams from which the strips were extracted.

: It should be noted that the tensile load capacity of CFRP strips / unit width (0.5 inch wide) used as a basis for comparison. Stress computation using fiber volume fraction or resin thickness is avoided.

Table 5-23 Tension test results of strips extracted from beams aged in water (9 months)

Age (months)	Temp (F)	Sample	Maximum load (kips)	Max Load (kips)		Stiffness (Msi)
				Avg.	SD (%)	
9	room	B2/1	1.450	1.500	3.33	31.9
		B2/2	1.550			
		B2/3	1.600			
	room	B4/1	1.160	1.483	15.44	31.3
		B4/2	1.500			
		B4/3	1.500			
	room	B5/1	1.400	1.543	9.72	32.2
		B5/2	1.530			
		B5/3	1.700			
	110	E1/1	1.610	1.553	3.54	30.9
		E1/2	1.500			
		E1/3	1.550			
	110	E2/1	1.650	1.383	22.1	29.8
		E2/2	1.450			
		E2/3	1.050			
	140	D1/1	1.250	1.300	3.85	31.2
		D1/2	1.350			
		D1/3	1.300			
	140	D2/1	1.500	1.450	9.10	29.5
		D2/2	1.550			
		D2/3	1.300			
	140	D4/1	1.250	1.300	3.85	29.9
		D4/2	1.350			
		D4/3	1.300			

Note : Sample B1, E3 etc. correspond to the beams from which the strips were extracted.

: It should be noted that the tensile load capacity of CFRP strips / unit width (0.5 inch wide) used as a basis for comparison. Stress computation using fiber volume fraction or resin thickness is avoided.

Table 5-24 Avg. tension test results of strips extracted from beams aged in water (9 months)

Age (months)	Temp (°F)	Avg. maximum load (kips)	SD (%)	Stiffness (Msi)
9	Room	1.509	9.48	31.8
	110°F	1.468	12.26	30.4
	140°F	1.350	5.70	30.2

Table 5-25 Tension test results of independent strips aged in water (9 months)

Age (months)	Temp (F)	Sample	Maximum load (kips)	Max Load (kips) Avg.	Max Load (kips) SD (%)	Stiffness (Msi)
9	room	room/1	1.500	1.533	3.72	32.1
		room/2	1.600			
		room/3	1.550			
	110	110/1	1.600	1.483	8.49	31.1
		110/2	1.350			
		110/3	1.500			
	140	140/1	1.300	1.417	14.26	31.0
		140/2	1.650			
		140/3	1.300			

Note : These independent CFRP strips were not attached to beams.
: It should be noted that the tensile load capacity of CFRP strips / unit width (0.5 inch wide) used as a basis for comparison. Stress computation using fiber volume fraction or resin thickness is avoided.

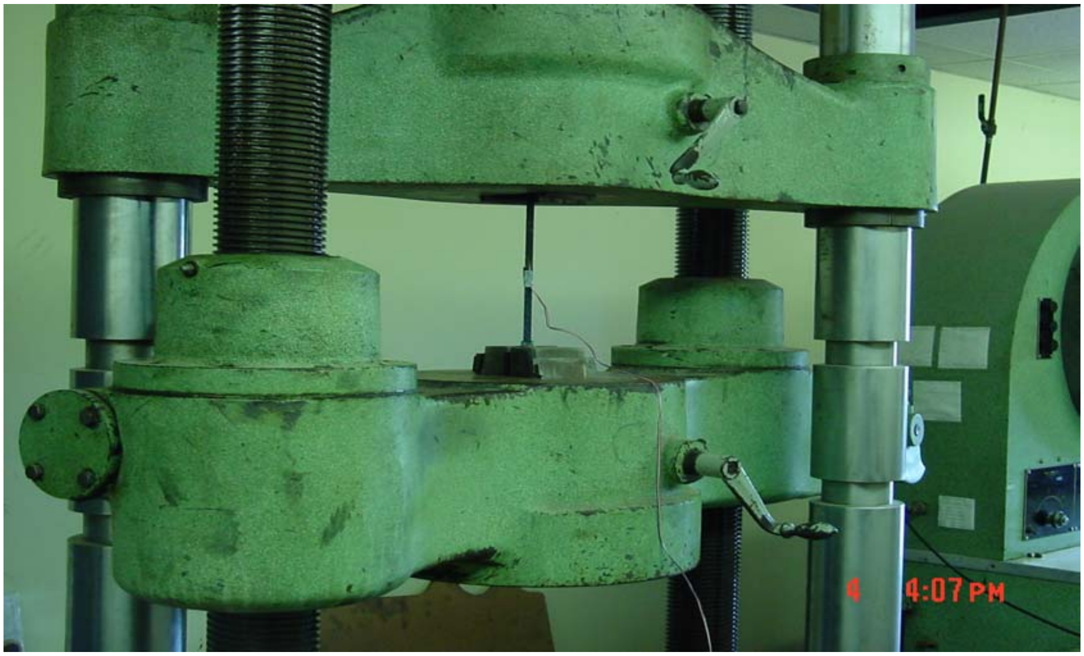

Fig 5.16 Tension test for carbon fiber strips

5.4.1 Tensile strength and stiffness of CFRP strips

CFRP strips were extracted from wrapped beams after testing the beams to failure. Maximum average tensile strengths of strips from wrapped beams under water at elevated temperatures are between 1350 to1550 lbs. In addition, average tensile stiffness values of strips are between 30.2 to 32.1Msi. The reductions in strength and stiffness were found by comparing these values to those at room temperature without aging, as shown in Table 5-26.

The strength and stiffness reduction of carbon fiber strips extracted from beams aged under water at room, 110°F and 140°F temperatures are:

At 3 months: from 0 to 10.19 % and from 1.869 to 2.18 %, respectively.

At 6 months: from 3.23 to 10.77 % and from 0 to 3.12 %, respectively.

At 9 months: from 2.65 to 12.90 % and from 0.935 to 5.92 %, respectively.

The average tensile strength and stiffness versus aging duration of carbon fiber strips extracted from beams under water are presented in Figure 5.17 and 5.18.

Compared to unaged strips, maximum reduction in strength and stiffness of strips extracted from beams aged in water at 140 °F temperatures was 12.90% and 5.92%, respectively.

Table 5-26 Average tensile strength/stiffness and reduction in strength/stiffness for CFRP strips extracted from beams aged in water

Age (months)	Average tensile strength and stiffness						% Reduction in strength/stiffness *(compared with 0 month specimens)					
	Temperature (F)						Temperature (F)					
	Room		110		140		Room		110		140	
	Strength (kips)	Stiffness (Msi)	Strength (kips)	Stiffness (Msi)	Strength (kips)	Stiffness (Msi)	Strength (%)	Stiffness (%)	Strength (%)	Stiffness (%)	Strength (%)	Stiffness (%)
0	1.550	32.1	-	-	-	-	-	-	-	-	-	-
3	1.550	31.5	1.483	31.4	1.392	31.4	0	1.869	4.32	2.18	10.19	2.18
6	1.500	32.0	1.473	31.3	1.383	31.1	3.23	0.312	4.97	2.49	10.77	3.12
9	1.509	31.8	1.468	30.4	1.350	30.2	2.65	0.935	5.29	5.30	12.90	5.92

Note: width of strips tested 0.5 inch

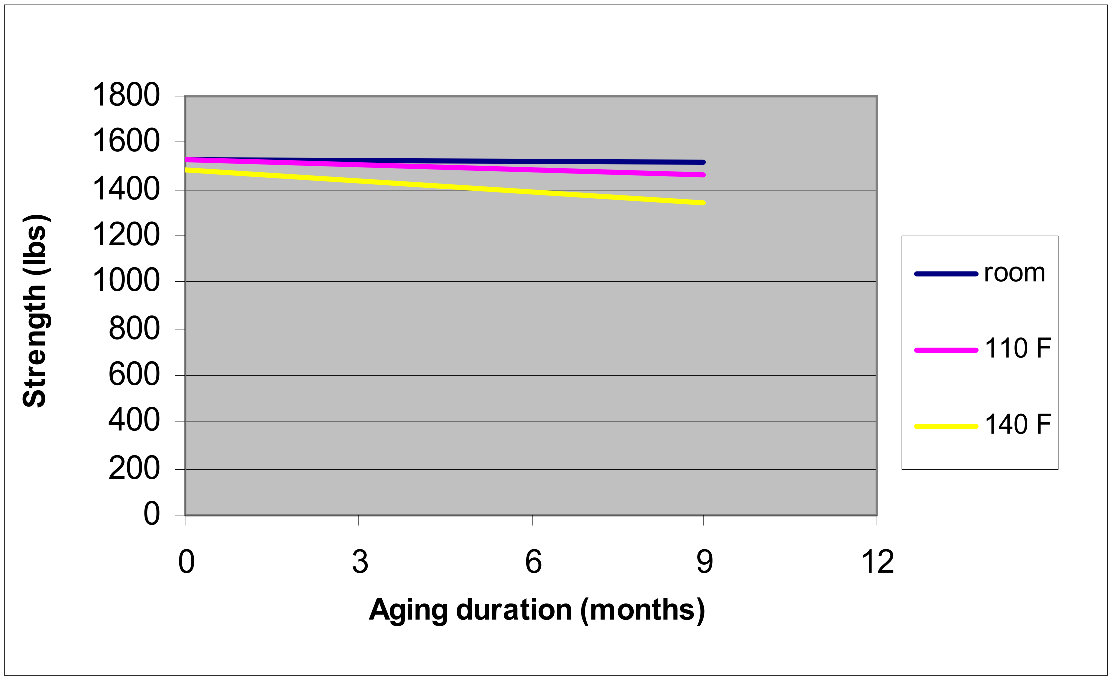

Fig 5.17 Strength of CFRP strips extracted from beams aged in water

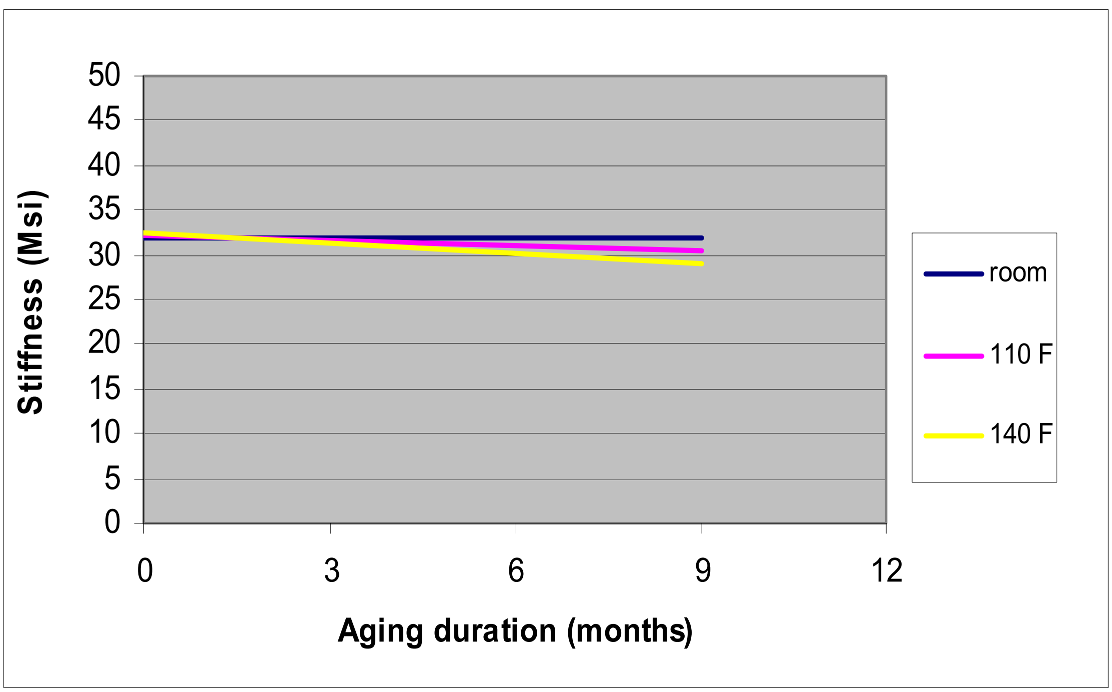

Fig 5.18 Stiffness of CFRP strips extracted from beams aged in water

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Table 5-27 Strength reduction of CFRP strips aged with and without attaching to concrete beams (9 months)

Age (months)	Temp (F°)	Avg. maximum load from strips with out extracted from beams (kips)	Avg. maximum load from strips extracted from beams (kips)	% reduction of tensile strength
9	room	1.533	1.509	0.625
	110°F	1.483	1.468	1.011
	140°F	1.417	1.350	2.27

Table 5-28 Stiffness reductions of CFRP strips aged with and without attaching to concrete beams (9 months)

Age (months)	Temp (F°)	Avg. maximum stiffness from strips with out extracted from beams (Msi)	Avg. maximum stiffness from strips extracted from beams (Msi)	% reduction of tensile stiffness
9	room	32.1	31.8	0.935
	110°F	31.1	30.4	2.25
	140°F	31.0	30.2	2.58

From Table 5.27 and 5.28, CFRP strips aged in water without bonding to concrete beams up to 9 months and 140 °F temperature show a maximum strength and stiffness less than 2.88% as compared to those bonded to concrete beams.

5. 5 RESULTS AND ANALYSIS OF BEAMS AGED UNDER ALKALINE AND SALT SOLUTION AT ROOM TEMPERATURE

Results from carbon wrapped beams measuring 5”×8”×60”aged in alkaline and salt solutions for 3 months are presented in terms of maximum failure load, maximum moment, maximum deflection (recorded) and maximum crack width (recorded) in Table 5-29.

Table 5-29 Three-point bending test results for beams aged in alkaline and salt solutions

Age (month)	Solution and Temp (F)	Beam	Wrap* Type	Max load (recorded) (kips)	Max. Moment (recorded) (Kip-ft)	Max deflection (recorded) (in)	Max crack-width (recorded) (in)
3	alkaline (room 68 °F)	A6	B	11.99	12.49	0.400	0.03
		A7	Bs	16.25	16.93	0.389	-
	salt (room 68 °F)	C2	B	12.46	12.98	0.455	0.024
		B9	Bs	17.02	17.73	0.523	-

Note: *b: one longitudinal layer of carbon fiber wrap at the beam bottom (full length)
bs: two sheets of longitudinal carbon fiber wraps at bottom and both sides along the length of beams (full length)
Max deflection and crack width (recorded) correspond to values between 70 to 100 % of maximum load and varied in each beam test.

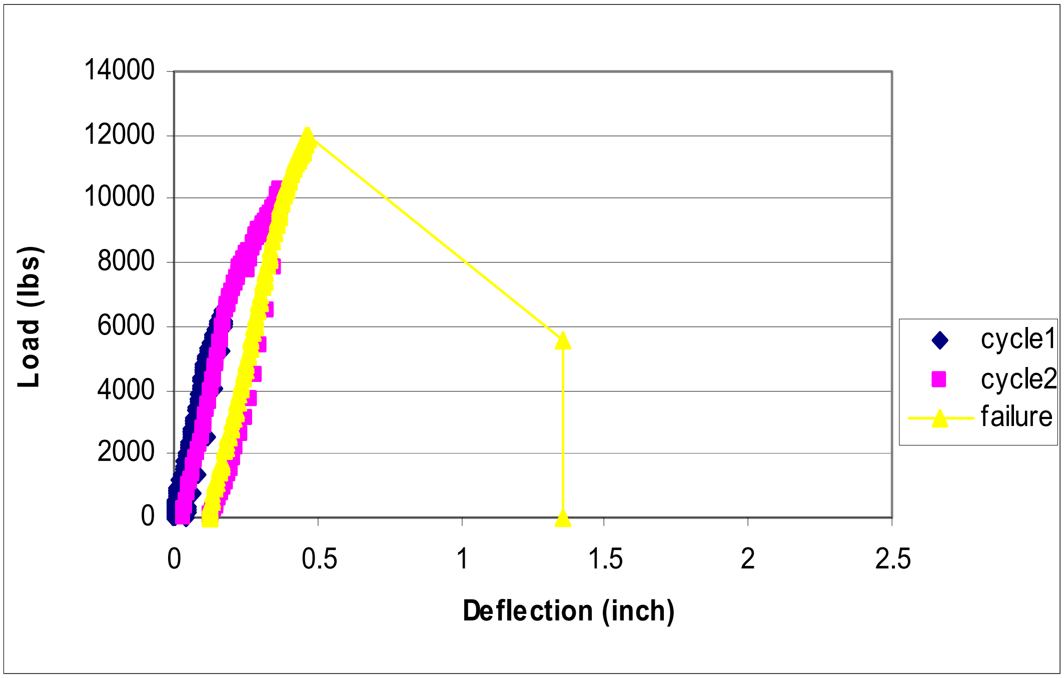

Fig 5.19 Load and deflection curve for beams aged in alkaline solution (room temperature for 3 months)

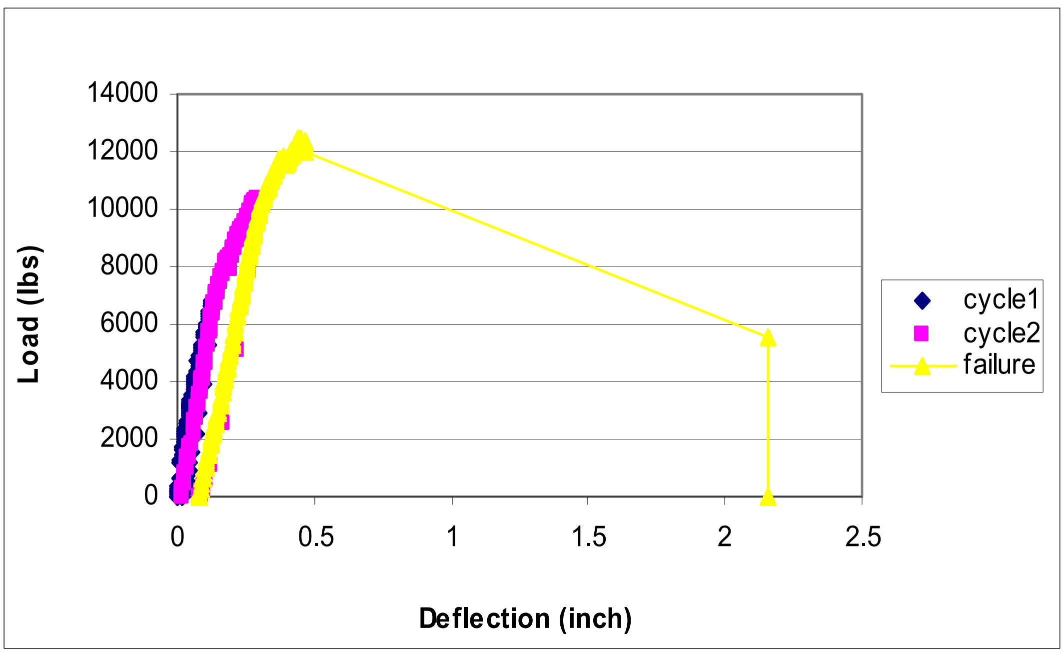

Fig 5.20 Load and deflection curve for beams aged in salt solution (room temperature for 3 months)

5.5.1 Load (moment) capacity

Maximum load and moment capacity of wrapped beams aged in alkaline and salt solutions until 3 months are higher than the theoretical values for all beams as shown in Table 5-30. The experimental to theoretical load (moment) ratios of wrapped beams A6 and A7 aged under alkaline solution at room temperature for 3 months are 1.153 and 1.181. The experimental to theoretical load (moment) ratios of wrapped beams C2 and B9 aged under salt solution at room temperature for 3 months are 1.207 and 1.259.

Maximum load capacities of beams aged under alkaline solution are slightly lower than those values for beams aged under salt solution for both types of bottom and U-shaped wrapping. [Table 5-30].U-shape wrapped beams performed better than those with bottom wraps in term of improved load capacity with the additional barrier it provides against moisture ingress. Maximum experimental to theoretical load ratio in U–shape wrapped beams increased by 4.68 % and 6.60% for alkaline and salt conditioning, respectively, as compared to bottom wrapped beams.

- 1.153 in alkaline solution for bottom wrapped beam versus 1.207 in alkaline for U-shape wrapped beam (4.68% increase)
- 1.181 in alkaline solution for bottom wrapped beam versus 1.259 in alkaline for U-shape wrapped beam (6.60% increase)

Table 5-30 Maximum (Exptl./Theor) load ratio of beams aged in alkaline and salt solution

Solution	Beam	Age (months)	Wrap* Type	Max load (Exptl.) (kips)	Max moment (Exptl.) (kip-ft)	Max load (Theor.) (kips)	Max moment (Theor.) (kip-ft)	Max load ratio (Exptl./Theor)
alkaline (room)	A6	3	B	11.90	12.39	10.32	10.75	1.153
	A7	3	Bs	16.25	16.93	13.80	14.34	1.177
Salt (room)	C2	3	B	12.46	12.98	10.32	10.75	1.207
	B9	3	Bs	17.02	18.04	13.80	14.34	1.233

Note: *b: one longitudinal layer of carbon fiber wrap at the beam bottom
bs: two sheets of longitudinal carbon fiber wrap at bottom and both sides along the length of beams

5.5.2 Deflection

Deflection values of each beam for different serviceability deflection limits specified by ACI 318-02 are obtained from experimental results and compared in Table 5-31.

Table 5-31 Loads at different limiting deflection values for wrapped beams in alkaline and salt solutions

Solution	Beam	Age (months)	Wrap* Type	Load at standard deflection limits (kips)		
				l/360 (0.1667 in)	l /240 (0.250 in)	l /180 (0.333in)
Alkaline (room)	A6	3	b	6.03	8.11	9.30
	A7		bs	9.05	11.65	12.81
Salt (room)	C2		b	7.18	8.93	10.52
	B9		bs	9.47	12.49	14.81

Note: *b: one longitudinal layer of carbon fiber wrap at the beam bottom
bs: two sheets of longitudinal carbon fiber wrap at bottom and both sides along the length of beams
Test span for three-point bending = 50 inch
Beam dimension: 5” ×8” × 60”

Table 5-32 Ratio of load at limiting serviceability deflection to maximum load

Solution	Beam	Load at deflection (span/360) to Max load]	[Load at deflection (span/240) to Max load]	Load at deflection (span/180) to Max load
Alkaline	A6	0.506	0.682	0.782
	A7	0.557	0.717	0.788
salt	C2	0.576	0.716	0.844
	B9	0.548	0.724	0.855

Ratio of load at limiting deflection (l/360, l/240 and l/180) to maximum load was lower in alkaline solution by a maximum of 12.15% as compared to salt conditioning during 3 months of aging. Alkaline solutions have resulted in slightly higher deflection reduction, which is attributed to the attack on bond line interface between the wrap and concrete.

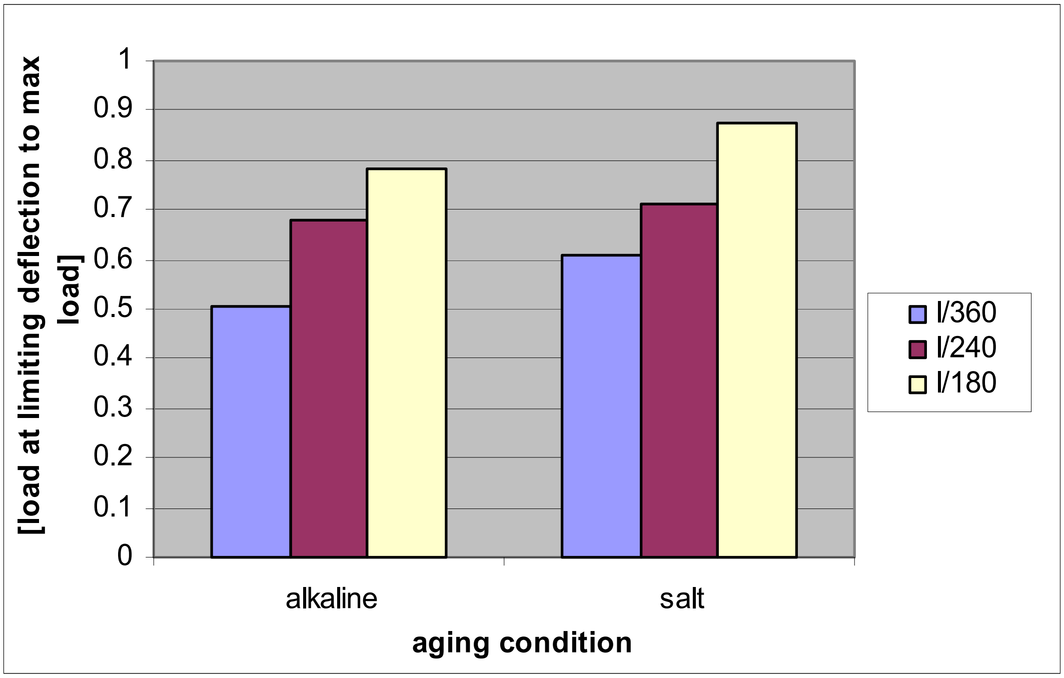

Fig 5.21 Load at limiting deflection to maximum load of beams for different aging conditions (3 months)

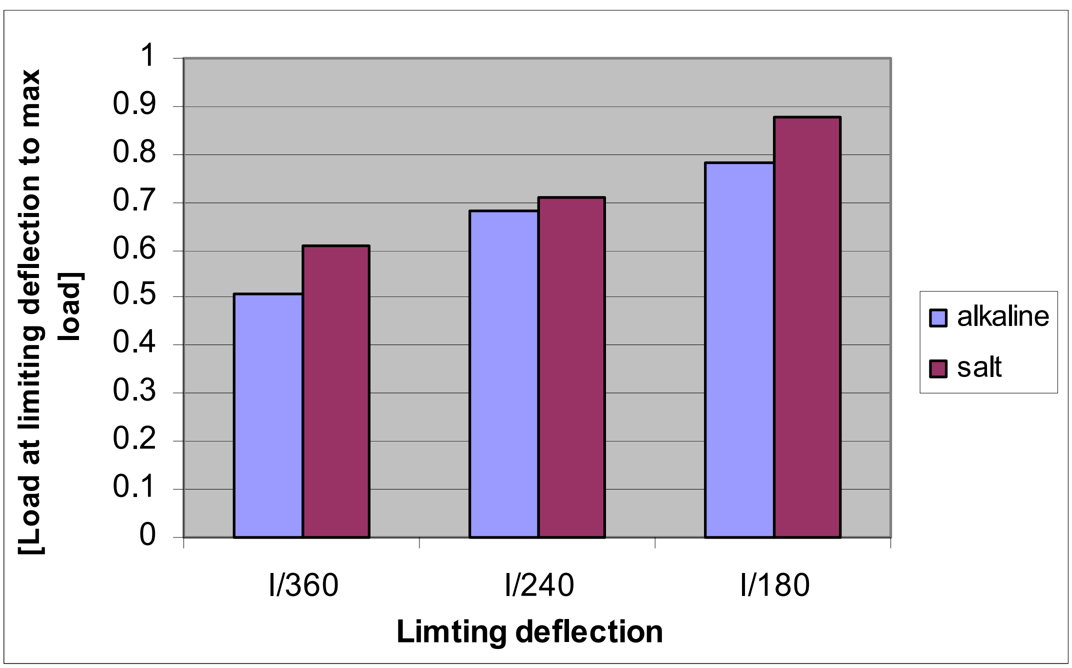

Fig 5.22 Load at limiting deflection to maximum load of beams for different limiting deflections (3 months)

Table 5-33 Load at crack width limit (0.016) of beams aged in alkaline and salt solution

Solution	Beam	Age (months)	Wrap* Type	Load (kips) at limiting crack width	Load at limiting crack width(0.016 in) to Max load
alkaline	A6	3 (room temperature)	B	7.00	0.588
salt	C2		B	7.80	0.626

Note: *b: one longitudinal layer of carbon fiber wraps at the beam bottom

Compared to salt conditioning at room temperature, ratio of load at limiting crack-width (0.016”) to maximum load for alkaline conditioning was less than 6.07% during 3 months of aging. Alkaline solutions have resulted in slightly higher crack-width reduction, which is attributed to the attack on bond line interface between the wrap and concrete.

5.5.3 Deformability factor

Ductility and deformability of reinforced concrete beams are explained in section 5.4.3.The deformability factors of wrapped beams under alkaline and salt solutions at room temperature for 3 months are between13.14 -15.93 and between13.29 -16.67 respectively. The deformability factors of wrapped beams aged in alkaline solution at room temperatures are lower than those for beams aged in salt solution for both types of bottom and U-shaped wrapping. The deformability factors are presented in Table 5-34.

Table 5-34 Maximum (Exptl./Theor) load ratio and deformability factor for beams aged in alkaline and salt solutions

Type	Beam	Age (months)	Wrap* Type	Max load (Exptl.) (kips)	Max def (Exptl.) (in)	Max load ratio (Exptl./Theor.)	Deformability (A_u/A_e)
alkaline	A6	3	b	11.90	0.400	1.153	13.14
	A7	3	bs	16.25	0.389	1.177	15.93
salt	C2	3	b	12.46	0.455	1.207	13.29
	B9	3	bs	17.02	0.523	1.233	16.67

Note: *b: one longitudinal layer of carbon fiber wraps at the beam bottom
bs: two sheets of longitudinal carbon fiber wrap at bottom and both sides along the length of beams
Test span for three-point bending = 50 in
Beam dimension: 5” ×8” × 60
$\mathbf{A_u}$ = area under load-deflection curve at ultimate load capacity
$\mathbf{A_e}$ = area under load-deflection curve at serviceability deflection limit, governing minimum value from (l/180) or crack width of 0.016in

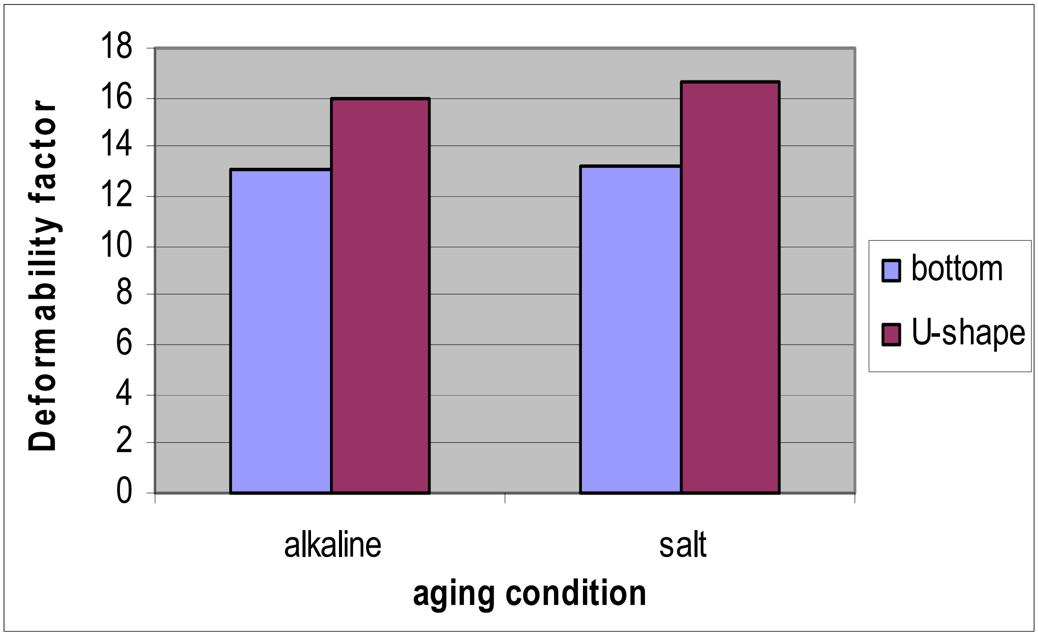

Fig 5.23 Deformability factors of wrapped beams aged in alkaline and salt solutions (room temperature for 3 months)

U-shaped wrapping provided better deformability and durability compared to one side bottom wrapping. U-shaped wrap helps in providing better bond, protecting the inner reinforcing (steel) bars in a cracked section against moisture ingress and bond line attack at the wrap-concrete interface.

5.6 RESULTS AND ANALYSIS OF CFRP STRIPS EXTRACTED FROM BEAMS AGED IN SALT AND ALKALINE SOLUTIONS AT ROOM TEMPERATURE

CFRP strips were extracted from wrapped beams aged in alkaline and salt solution (refer to section 5.5) at room temperature for 3 months after conducting three-point bending test. The carbon fiber strips used for specimen preparation were selected such that any damaged or ruptured sections were avoided. The results in terms of fabric tensile strength and stiffness are presented in Table 5-35.

Table 5-35 Tension test results of CFRP strips extracted from beams aged in alkaline and salt solutions

Age (months)	Solution	Sample	Maximum load (kips)	Max Load (kips)		Stiffness (Msi)
				Avg.	SD (%)	
3 (room)	alkaline	A6/1	1.500	1.467	3.61	30.5
		A6/2	1.400			
		A6/3	1.500			
	alkaline	A71	1.350	1.433	10.05	30.1
		A7/2	1.350			
		A7/3	1.600			
	salt	C2/1	1.550	1.483	5.12	30.8
		C2/2	1.500			
		C2/3	1.400			
	salt	B9/1	1.550	1.450	5.97	30.1
		B9/2	1.400			
		B9/3	1.400			

Note : sample A6, A7 etc. correspond to the beams from which the strips were extracted.
: It should be note that the tensile load capacity of CFRP strips / unit width (0.5 inch wide) used as a basis for comparison. Stress computation using fiber volume fraction or resin thickness is avoided.

5.6.1 Tensile strength and stiffness of CFRP strips

Average tensile strength and stiffness of CFRP strips extracted from beams aged in alkaline and salt solutions at room temperature for 3 months were between 1.425 -1.467 kips and between 30.3 -30.5 Msi, respectively. The average tensile strength and stiffness values of CFRP strips extracted from beams aged in alkaline and salt solution are slightly lower than the unaged CFRP strips. The strength and stiffness reduction of strips extracted from beams aged under alkaline and salt solution immersion at room temperature were a maximum of 6.45% and 5.61%, respectively, as shown in Table5-36. In addition, compared with strips extracted from beams aged in water at room temperature for 3 months, strength and stiffness reduction of strips extracted from beams aged in alkaline and salt solutions at room temperature were a maximum of 6.45% and 3.81%, respectively, as shown in Table 5-37.

Fig 5.24 Tension test on CFRP strips extracted from beams aged in alkaline solution (room temperature for 3 months)

Table 5-36 Average tensile strength/stiffness and reduction in strength/stiffness for CFRP strips

Age (months)	Average tensile strength and stiffness				Reduction in strength and stiffness *(compared to 0 month specimens)			
	Solution				solution			
	alkaline		Salt		alkaline		salt	
	Strength (Kips)	Stiffness (Msi)	Strength (Kips)	Stiffness (Msi)	Strength (%)	Stiffness (%)	Strength (%)	Stiffness (%)
3 (room)	1.450	30.3	1.467	30.5	6.45	5.61	5.35	4.98

Note: * Strength from 0 month carbon fiber strips = 1.550 kips
* Stiffness from 0 month carbon fiber strips= 32.1 Msi

Table 5-37 Comparison of average tensile strength/stiffness and reductions in strength/stiffness for CFRP strips extracted from beams aged in alkaline and salt solution

Solution	Tensile strength and stiffness		Reduction in strength compared to strips (water, 3 months	
	Strength (Kips)	Stiffness (Msi)	Strength (%)	Stiffness (%)
water(room)	1.550	31.5	-	-
Alkaline	1.450	30.3	6.45	3.81
Salt	1.467	30.5	5.35	3.17

5.7 RESULTS AND ANALYSIS OF BEAMS AGED IN ALKALINE AND SALT SOLUTION UNDER FREEZE-THAW CONDITIONING FOR 6 MONTHS

Results from carbon wrapped beams of 5”× 8”×60” aged in alkaline and salt solutions under freeze-thaw conditioning for 6 months are presented in terms of maximum failure load, maximum moment, maximum deflection (recorded) and maximum crack width (recorded) in Table 5-38.

Table 5-38 Three-point bending test results of beams aged in alkaline and salt solutions under freeze-thaw conditioning

Age (month)	Solution	Beam	Wrap* Type	Max load (recorded) (kips)	Max. Moment (recorded) (kip-ft)	Max deflection (recorded) (in)	Max crack-width (recorded) (in)
6	Alkaline	C4	b	9.06	9.44	0.380	0.023
	Alkaline	C8	bs	17.09	18.01	0.481	-
	Salt	C1	b	10.75	11.20	0.454	0.025
	Salt	C10	bs	17.45	18.70	0.526	-

***Note**: b: one longitudinal layer of carbon fiber wrap at the beam bottom
bs: two sheets of longitudinal carbon fiber wraps at bottom and both sides along the length of beams
Max deflection and crack width (recorded) correspond to values between 70 to 100 % of maximum load and varied in each beam test.

5.7.1 Load (moment) capacity

Maximum load and moment capacity of wrapped beams aged in alkaline and salt solution under freeze-thaw conditioning for 6 months are higher than the theoretical values except for beam C4. The experimental/theoretical load (moment) ratios of wrapped beams C4 and C8 aged in alkaline solution under freeze-thaw conditioning for 6 months are 0.878 and 1.257, respectively. Alkaline solution aging produced few cracks with larger widths whereas cracks due to salt conditioning were more uniform with lesser widths. In effect, alkaline solution weakens a section (e.g., mid span) more than the salt solution and leads to failure at comparatively lower loads.

The experimental/theoretical load (moment) ratios of wrapped beams C1 and C10 aged in salt solution under freeze-thaw conditioning for 6 months are 1.042 and 1.305, respectively.

Maximum load capacities of beams aged in alkaline solution are slightly lower than those aged in salt solution for both types of bottom and U-shaped wrapping. The results of maximum load, maximum moment and maximum load (moment) ratios are presented in Table 5-39.

Table 5-39 Maximum (Exptl./Theor) load ratio of beams aged in alkaline and salt solutions under freeze-thaw conditions

Solution	Beam	Age (months)	Wrap* Type	Max load (Exptl.) (kips)	Max moment (Exptl.) (kip-ft)	Max load (Theor.) (kips)	Max moment (Theor.) (kip-ft)	Max load ratio (Exptl./Theor)
alkaline	C4	6	b	9.06	9.44	10.32	10.75	0.878
	C8	6	bs	17.09	18.01	13.80	14.34	1.238
salt	C1	6	b	10.75	11.20	10.32	10.75	1.042
	C10	6	bs	17.45	18.70	13.80	14.34	1.264

Note: * b: one longitudinal layer of carbon fiber wrap at the beam bottom
bs: two sheets of carbon fiber wrap at bottom and both sides along the length of beams

5.7.2 Deflection

Deflection values of each beam for different serviceability deflection limits specified by ACI 318-02 are obtained from experimental results and compared as shown in Table 5-40.

Table 5-40 Loads at different limiting deflection values of beams aged in alkaline and salt solution under freeze-thaw conditions

Solution	Beam	Load at deflection (span/360) to Max load	Load at deflection (span/240) to Max load	Load at deflection (span/180) to Max load
alkaline	C4	0.613	0.745	0.795
	C8	0.615	0.750	0.844
salt	C1	0.672	0.748	0.842
	C10	0.665	0.756	0.847

Note: *b: one longitudinal layer of carbon fiber wrap at the beam bottom
bs: two sheets of longitudinal carbon fiber wrap at bottom and both sides along the length of beams
Test span for three-point bending = 50 inch
Beam dimension: 5” ×8” × 60”

Table 5-41 Load at serviceability deflection limits to maximum load ratio

Solution	Beam	Age (months)	Wrap* Type	Load at standard deflection limits (lbs)		
				l/360 (0.1667 in)	l/240 (0.250 in)	l/180 (0.333in)
A	C4	6	b	5.55	6.75	7.20
	C8		bs	10.64	12.96	14.58
S	C1		b	7.32	8.05	9.05
	C10		bs	11.94	13.57	15.20

Note *b: one longitudinal layer of carbon fiber wrap at the beam bottom
bs: two sheets of longitudinal carbon fiber wrap at bottom and both sides along the length of beams
Test span for three-point bending = 50 inch
Beam dimension: 5” ×8” × 60”

Ratio of load at limiting deflection (l/360, l/240 and l/180) to maximum load was lower in alkaline solution by a maximum of 8.77% as compared to salt conditioning during 6 months of aging. Alkaline solutions have resulted in slightly higher deflection reduction, which is attributed to the attack on bond line interface between the wrap and concrete.

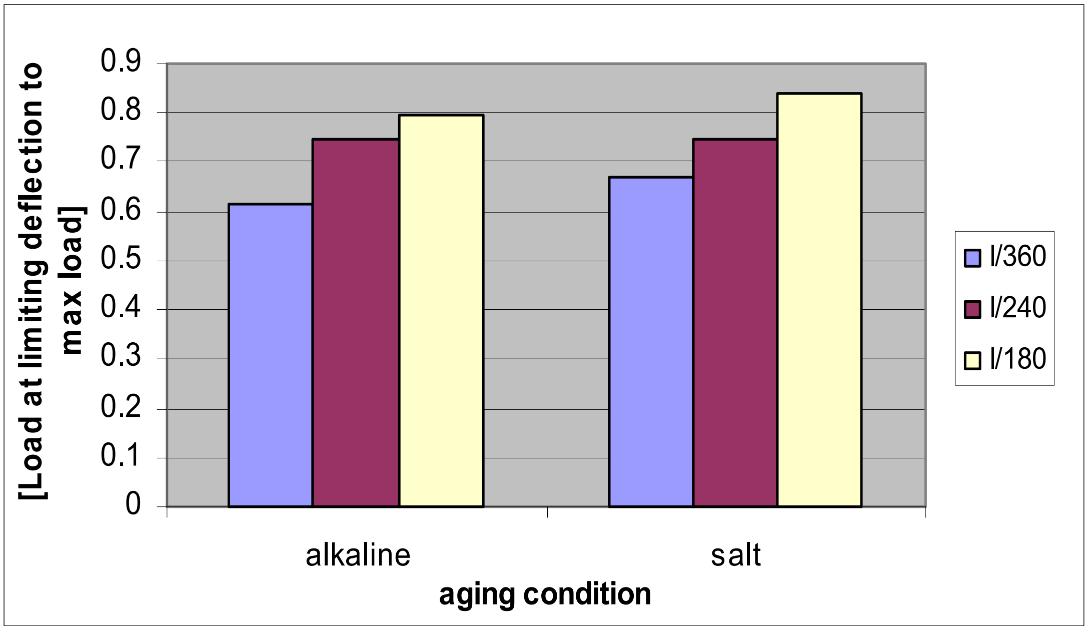

Fig 5.25 Load at limiting deflection to maximum load of beams aged in alkaline and salt solution under freeze-thaw conditioning

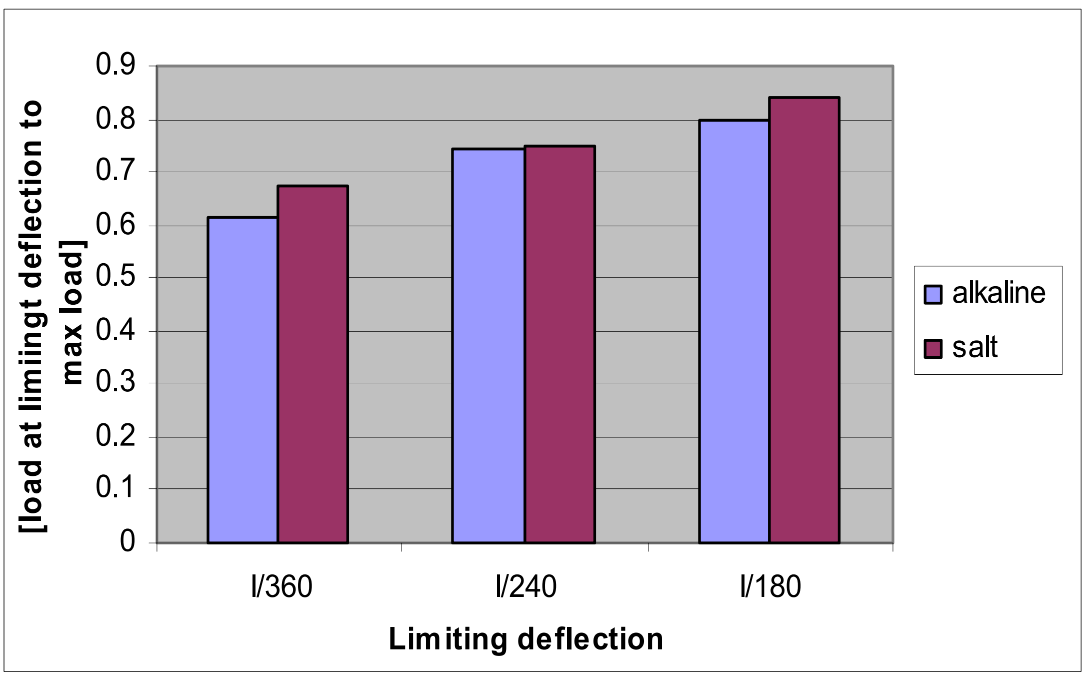

Fig 5.26 Load at limiting deflection to maximum load of beams aged in alkaline and salt solution under freeze-thaw conditioning

Table 5-42 Loads at limiting crack width (0.016 in) of beams aged in alkaline and salt solution under freeze-thaw conditioning

Solution	Beam	Age (months)	Wrap* Type	Load at limiting crack width (0.016 in) (kips)	Load at limiting crack width (0.016in) to Max load
alkaline	C4	6	b	7.00	0.652
salt	C1	6	b	7.00	0.773

Note: *b: one longitudinal layer of carbon fiber wrap at the beam bottom

Compared to salt conditioning under freeze-thaw conditioning, ratio of load at limiting crack-width (0.016") to maximum load for alkaline conditioning was not greater than 15.65% during 6 months of aging. Alkaline solutions have resulted in slightly higher crack-width reduction, which is attributed to the attack on bond line interface between the wrap and concrete.

5.7.3 Deformability factor

Ductility and deformability factor of reinforced concrete beams is explained in section 5.4.3. The deformability factors of wrapped beams aged in alkaline and salt solution under freeze-thaw conditioning at 6 months are between12.29-14.74 and between 14.09-15.62, respectively. The deformability factors of wrapped beams aged in alkaline solutions under freeze-thaw conditioning are lower than those values of wrapped beams aged under salt immersion for both types of bottom and U-shaped wrapping. The deformability factors are presented in Table 5-43.

Table 5-43 Maximum (Exptl./Theor) load ratio and deformability for beams aged in alkaline and salt solutions under freeze-thaw conditioning

Type	Beam	Age (months)	Wrap* Type	Max load (Exptl.) (kips)	Max def (Exptl.) (in)	Max load ratio (Exptl./Theor.)	Deformability (A_u/A_e)
alkaline	C4	6	b	9.06	0.380	0.878	12.29
	C8	6	bs	17.29	0.481	1.675	14.74
Salt	C1	6	b	10.75	0.454	1.042	14.09
	C10	6	bs	17.95	0.526	1.742	15.62

Note: *b: one longitudinal layer of carbon fiber wrap at the beam bottom (full length)
bs: two sheets of longitudinal carbon fiber wrap at bottom and both sides along the length of beams
Test span for three-point bending = 50 inch

A_u = area under load-deflection curve at ultimate load capacity
A_e = area under load-deflection curve at serviceability deflection limit of governing minimum value from (l/180) or crack width of 0.016in

U-shaped wrapping provided better deformability and durability compared to one side bottom wrapping. U-shaped wrap helps in providing better bond, protecting the inner reinforcing elements in a cracked section against moisture ingress and bond line attack at the wrap-concrete interface.

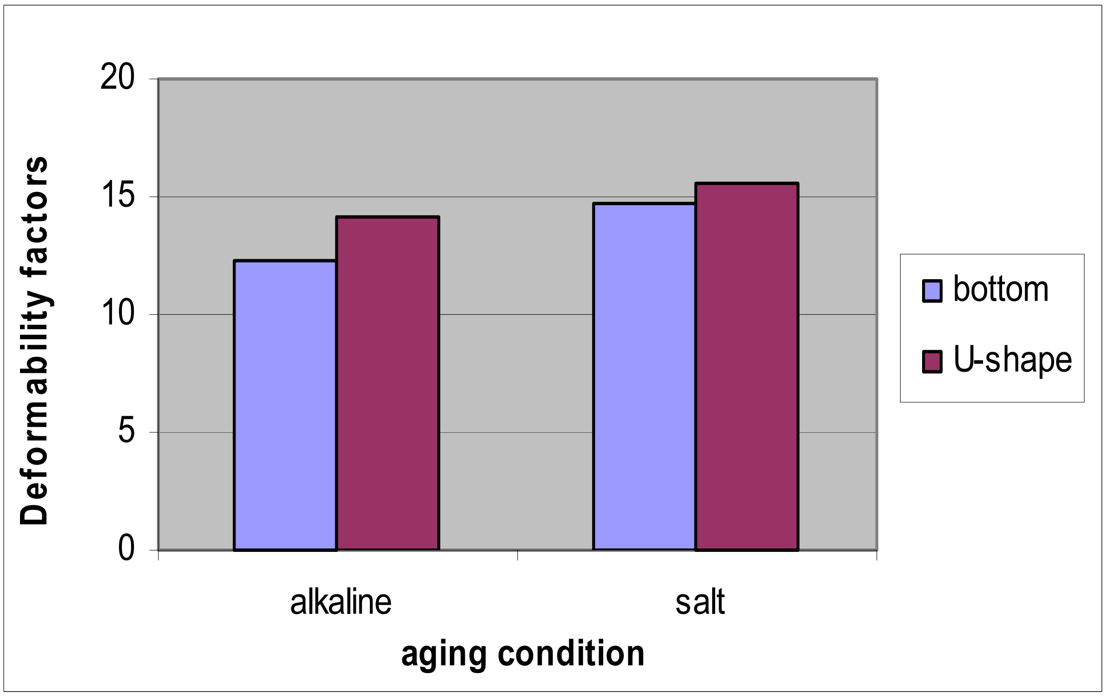

Fig 5.27 Deformability factors of beams aged in alkaline and salt solutions under freeze-thaw conditioning

5.8 RESULTS AND ANALYSIS OF CFRP STRIPS EXTRACTED FROM BEAMS AGED IN ALKALINE AND SALT SOLUTION UNDER FREEZE-THAW CONDITIONING

CFRP sheets were extracted after three-point bending tests from wrapped beams aged in alkaline and salt solution (refer to section 5.7) under freeze-thaw conditioning for 6 months. The results in terms of fabric tensile strength and stiffness are presented in Table 5-44.

Table 5-44 Tension test results of CFRP strips extracted from beams aged in alkaline and salt solutions under freeze-thaw conditioning

Age (months)	Solution	Sample	Maximum load (kips)	Max load (kips)		Stiffness (Msi)
				Avg.	SD (%)	
6 (freeze-thaw)	alkaline	C4/1	1.350	1.400	3.57	30.6
		C4/2	1.450			
		C4/3	1.400			
	alkaline	C8/1	1.400	1.400	3.57	29.1
		C8/2	1.350			
		C8/3	1.450			
	salt	C1/1	1.400	1.400	3.57	30.3
		C1/2	1.450			
		C1/3	1.350			
	salt	C10/1	1.500	1.467	10.06	29.1
		C10/2	1.300			
		C10/3	1.600			

Note: sample C4, C8 etc. correspond to the beams from which the strips were extracted.
: It should be noted that the tensile load capacity of CFRP strips / unit width (0.5 inch wide) used as a basis for comparison. Stress computation using fiber volume fraction or resin thickness is avoided.

.5.8.1 Tensile strength and stiffness of CFRP strips

Average tensile strength and stiffness of CFRP strips extracted from beams aged in alkaline and salt solution for 6 months under freeze-thaw conditioning between 1.4 -1.434 kips and between 29.7-29.9Msi, respectively.

The average tensile strength and stiffness values of strips extracted from beams aged in alkaline and salt solutions are slightly lower than unaged strips. The strength and stiffness reduction of carbon fiber strips extracted from beams aged under alkaline and salt solutions and also under freeze-thaw conditioning were a maximum of 9.68% and 7.48%, respectively. The results are shown in Table5-45.

In addition, compared with carbon fiber strips extracted from beams aged in water at room temperature for 6 months, strength and stiffness reduction of carbon fiber strips extracted from beams aged in alkaline and salt solution under freeze-thaw conditioning were a maximum of 6.67% and 7.48%, respectively, as given in Table 5-46.

Table 5-45 Average tensile strength/stiffness and reduction in strength/stiffness for CFRP strips

Age (months)	Avg.(3 samples) tensile strength and stiffness				Reduction in strength and stiffness *(compared to 0 month specimens)			
	Solution				Solution			
	alkaline		Salt		alkaline		salt	
	Strength (kips)	Stiffness (Msi)	Strength (kips)	Stiffness (Msi)	Strength (%)	Stiffness (%)	Strength (%)	Stiffness (%)
6 (freeze-thaw)	1.400	29.9	1.434	29.7	9.68	6.85	7.48	7.48

Note: * Strength from 0 month carbon fiber strips = 1.550 kips
*Stiffness from 0 month carbon fiber strips= 32.1 Msi

Table 5-46 Average tensile strength/stiffness and reduction in strength/stiffness for strips compared to CFRP strips (water, 6 months)

Solution	Avg.(3 samples) tensile strength and stiffness		Reduction in strength (compared to 6 month specimens)	
	Strength (kips)	Stiffness (Msi)	Strength (%)	Stiffness (%)
water(room)	1.500	32.1	-	-
alkaline	1.400	29.9	6.67	6.85
salt	1.434	29.7	4.40	7.48

5.9 RESULTS AND ANALYSIS OF WRAPPED AND NON-WRAPPED CONCRETE BEAMS

Two non-wrapped beams of 5”x 8”x 60” without any aging were tested under 3-point bending similar to the tests on wrapped beams and the results are listed in Appendix I, Tables I-1. Maximum increase in beam bending moment due to one layer of CFRP wrap was found to be 113.5% (12.79 kips for beam B5 in Table 5.6 as compared to average load of 5.99 kips in non-wrapped beams). Magnitude of moment capacity increase due to wrapping depends upon beam dimensions, internal reinforcement properties (e.g., area and yield strength), and number of carbon fiber wrap layers.

Similarly, loads to limiting deflection values and crack-widths showed significant increase of 75% or more in wrapped beams (typically, higher than 7 kips for l/360 limit from Table 5.13) as compared to beams without wrapping (typically, about 4 kips for l/360 from Appendix Table I-4). However, wrapping related increase in loads to reach limiting deflections and crack widths depends upon several factors discussed earlier.

Deformability factors of non-wrapped beams varied between10.47 to 10.93 (Table I-3). Wrapped beams also provided deformability factors higher than 10.

It should be noted that additional comparisons on moment (load) ratios, deflections and crack widths are carried out among wrapped and aged beams only.

5.10 STRUCTURAL RESPONSE FROM TEST DATA

5.10.1 Accelerated aging of wrapped concrete beams in water

Three-point bending test data were used to evaluate structural response of wrapped beams aged in water at room, 110° F, and 140°F temperatures. CFRP strips were extracted from aged carbon fabrics extracted from beams that were tested in beam bending and tested in tension.

Load (moment) capacity

- Average experimental load (moment) to theoretical load (moment) capacity of all the wrapped beams aged in water at elevated temperatures for 3, 6 and 9 months varied between 1.026 and 1.178 (Tables 5-4 to 5-6).
- Results of experimental to theoretical load (moment) ratios indicated a reducing trend in load (moment) capacity with increasing temperatures. Maximum reduction in experimental to theoretical load (moment) ratios for water aging at room, 110 ^{0}F and 140 ^{0}F during 9 months was 9.68%.

Deflection and crack width up to 2kip load (≈20% of Max. load)

- Deflection and crack width of wrapped beams in water at 2 kip load were observed to be clearly increasing with elevated temperature and aging duration.
- Increases in deflection and crack width at 140°F for 9 months of aging were 45.6 % and 28%, respectively.

Limiting deflection

- The ratios of load at each deflection limit (l/360, l/240 and l/180) to maximum load of beams aged in water for 3, 6 and 9 months decreased with both temperature and aging duration.

- Maximum reduction in the ratio of load at limiting deflection (l/360, l/240 and l/180) to maximum load for water aging at room, 110 ^{0}F and 140 ^{0}F during 9 months was 7.29%, when compared to either room temperature or beams aged for 3 months.

Limiting crack width (0.016 in)

- The ratios of load at limiting crack width (0.016 in) to maximum load of beams aged in water at elevated temperatures decreased with the increase of temperature and aging duration.
    - Maximum reduction in the ratio of load at limiting crack-width (0.016”) to maximum load for water aging at room, 110 ^{0}F and 140 ^{0}F during 9 months was 7.98%, when compared to either room temperature or beams aged for 3 months.

Deformability factor

- From wrapped beam-bending test, the average deformability factors of wrapped beams aged in water immersion at room, 110°F and 140°F temperatures varied between 10.09 and 14.74 during 9 months of aging.
- The average deformation factors decreased with increase in temperature and aging duration.
- Compared to room temperature, reduction in average deformability factor at 110 °F and 140 °F was 7.29 % and 12.91%, respectively during the 9 month aging.

Strength and stiffness of Carbon fiber strips

- The strength and stiffness reduction were a maximum of 12.90 % and 5.92 %, respectively, (Table 5-28).

5.10.2 Accelerated aging of wrapped concrete beams in alkaline and salt solution at room temperature

Three-point bending tests were conducted on wrapped beams aged in alkaline (pH ≅ 13) and salt (pH ≅ 7) solutions at room temperature for 3 months. CFRP strips were extracted from aged beam after conducting bending tests.

Load (moment) capacity

- Average experimental load to theoretical load (moment) capacities for all wrapped concrete beams aged in alkaline and salt solutions at room temperature for 3 months were between 1.153 and 1.259 (Table 5-30). Maximum load capacities of beams aged in alkaline solutions are slightly lower than those aged in salt solution for both types of bottom and U-shaped wrapping. U-shape wrapped beams performed better than those of bottom wrapped beams in term of improved load capacity with additional barrier the wrap provides against moisture ingress. Maximum experimental to theoretical load ratio in U–shape beams increases 4.68 % and 6.60% for alkaline and salt conditioning, respectively, as compared to beams with bottom only.

Limiting deflection

- Ratio of load at limiting deflection ($l/360$, $l/240$ and $l/180$) to maximum load was lower in alkaline solution by a maximum of 12.15% as compared to salt conditioning during 3 months of aging.

Limiting crack width (0.016 in)

- Ratio of load at limiting crack-width (0.016”) to maximum load was lower in alkaline solution by a maximum of 6.07% as compared to salt conditioning during 3 months of aging.

Deformability factor

- The deformability factors of wrapped beams in alkaline and salt solutions at room temperature at 3 months varied between13.14 to 15.93 and between13.29 to 16.67, respectively (Table 5-34).

- The deformability factors of beams aged under alkaline solution immersion are slightly lower than those for beams aged under salt solutions for both types of bottom and U-shaped wrapping. Increased deformability factors in U-shape wrapped beams are mainly due to increased moment capacities providing additional energy absorption capability.

    - 13.14 in alkaline solution versus 13.29 in salt solution for bottom wrapped beam
    - 15.93 in alkaline solution versus 16.67 in salt solution for U-shape wrapped beam

Strength and stiffness of carbon fiber strips

- The strength and stiffness reduction under alkaline and salt solutions for 3 months were a maximum of 6.45% and 5.61%, respectively (Table 5-36).

- Reduction in strength and stiffness under different solutions at room temperature for 3 months

    - *Reduction due to water condition*: strength 0% : stiffness1.869% (Table 5-28)
    - *Reduction due to alkaline condition*: strength 6.45% : stiffness 5.61%(Table 5-36)
    - *Reduction due to salt condition*: strength 5.35% : stiffness 4.98% (Table 5-36)

5.10.3 Accelerated aging of wrapped concrete beams in alkaline and salt solution at freeze-thaw conditioning

Three-point bending tests were conducted on wrapped beams aged in alkaline (pH ≅ 13) and salt (pH ≅ 7) solutions in freeze-thaw conditioning for 6 months. CFRP strips were extracted from aged beam after conducting on bending tests.

Load (moment) capacity

- Average ratios of experimental to theoretical load (moment) capacity of all wrapped concrete beams aged in alkaline and salt solutions under freeze-thaw conditions for 6 months varied between 1.042 and 1.305 except for beam C4 (Table 5-39).
- Maximum load capacities of beams aged in alkaline solution are slightly lower than those for beams aged in salt solutions for both types of bottom and U-shaped wrapping.

Limiting deflection

- Ratio of load at limiting deflection ($l/360$, $l/240$ and $l/180$) to maximum load was lower in alkaline solution by a maximum of 8.77% as compared to salt conditioning during 6 months of aging.

Limiting crack width (0.016 in)

- Ratio of load at limiting crack-width (0.016”) to maximum load was lower in alkaline solution by a maximum of 15.65% as compared to salt conditioning during 6 months of aging.

Deformability factor

- The deformability factors of wrapped beams aged in alkaline and salt solutions under freeze-thaw conditioning for 6 months varied between12.29 to14.74 and between14.09 to 15.62, respectively, (Table 5-43).

- The deformability factors of beams aged in alkaline solutions are lower than those for beams aged in salt solution for both types of bottom and U-shaped wrapping (Table 5-43). Increased deformability factors in U-shape wrapped beams are mainly due to increased moment capacities providing additional energy absorption capability.

    - 12.29 in alkaline solution versus 14.09 in salt solution for bottom wrapped beam
    - 14.74 in alkaline solution versus 15.62 in salt solution for U-shape wrapped beam

Strength and stiffness of carbon fiber strips

- The strength and stiffness reduction under alkaline and salt solutions and also under freeze-thaw conditioning were a maximum of 9.68% and 7.48%, respectively, (Table 5-45).
- Reductions in strength and stiffness under different solutions and also under freeze-thaw conditioning for 6 months

    - *Reduction due to water condition*: strength 3.23% : stiffness 0.3% (Table 5-28)
    - *Reduction due to alkaline condition*: strength 9.68% : stiffness 6.85%(Table 5-45)
    - *Reduction due to salt condition*: strength 7.48% : stiffness 7.48% (Table 5-45)

Chapter 6

CONCRETE BEAM WRAPPED WITH CARBON SHEETS UNDER NATURAL AGING

6. 1 INTRODUCTION

Bending tests were conducted on naturally aged beams wrapped with carbon fiber sheets. Tension test were conducted on CFRP strips extracted from naturally aged beams after testing beams in bending. Results are presented in terms of strength, stiffness and serviceability aspects of wrapped beams aged under natural conditions.

The results from tests conducted on beams and CFRP strips are briefly described below.

6.1.1Natural aging at constant 68 °F for 3.5 years

Three-point loading tests were conducted on beams of 5”×6”×96” aged naturally for 3.5 years (constant 68°F). Carbon fiber strip specimens were extracted from carbon fabrics on concrete beams after the completion of aging and subsequent three-point bending tests on beams. CFRP strips were tested to evaluate aging related strength and stiffness variations.

6.1.2Natural aging under outside weathering for 3 years

Four-point bending tests were conducted on concrete beams of 6”×15”×120” aged under natural weathering for 3 years. During each year of natural aging in Morgantown, WV, the beams were subjected to freezing and thawing during winter, high and low temperature variation during summer, and temperature variation coupled with humidity variation during rainy (fall) season. After each aging period, the beams were brought back into the laboratory and the same four point bending tests were performed by loading them to 8,000 lbs (14 k-ft). Mid-span deflection and strain readings on the FRP wrap were recorded. CFRP strips were extracted from carbon fabrics on concrete beams after beam bending tests. The CFRP strips were attached with grips and tested to evaluate aging related strength and stiffness variation. Concrete is naturally alkaline (pH~13) and concrete structures are periodically subjected to deicing salts (pH~7), rainwater, free-thaw temperature and elevated temperature during summer. Hence, this study comprises of all the above aging elements that contribute to the structural deterioration.

6.2 OVERVIEW OF TEST RESULTS

Results of beams tested after natural aging conditions under bending are discussed in terms of maximum load capacity, maximum moment capacity, and maximum load ratio, deflection at mid span, crack width, and deformability.

Results of CFRP strips are compared as a percent of original (un-aged) values. Test results are presented in the format shown below under respective section numbers.

6.3 Results of beams aged under constant 68°F for 3.5 years are analyzed for:

6.3.1 Load (moment) capacity

6.3.2 Deflection of beams

6.3.3 Deformability factors

6.4 Results and analysis of CFRP strips extracted from beams at constant 68°F are analyzed for:

6.4.1 Tensile strength and stiffness

6.5 Results of beams under outside weathering for 3 years are analyzed for:

6.5.1 Load (moment) capacity, deformability and stiffness

6.6 Results of CFRP strips extracted from beams under outside weathering for 3 years are analyzed for:

6.6.1 Tensile strength and stiffness

6.3 RESULTS AND ANALYSIS OF BEAMS AGED AT CONSTANT 68°F FOR 3.5 YEARS

Results from beams of 5”× 6”×96”wrapped with one (beam b1and b3) and three (beam b2) longitudinal layers at the bottom of the beam under natural aging for 3.5 years are presented in terms of maximum failure load, maximum moment, maximum deflection (recorded) and maximum crack width (recorded) in Table 6-1.

Table 6-1 Three-point loading test results for beams aged at constant 68°F

Age (years)	Temp (F)	Beam	Wrap* Type	No. of longitudinal layers	Max load (recorded) (kips)	Max. Moment (recorded) (Kip-ft)
3.5	room	b1	B	1	6.25	10.94
		b2	B	3	9.65	16.89
		b3	B	1	5.91	10.35

***Note:** b: one longitudinal layer of carbon fiber wrap at the beam bottom
Test span for three-point bending = 84 inch

Fig 6.1 Three-Point loading test of wrapped beams (constant 68°F, 3.5 years)

(fabric rupture and debonding)

Fig 6.2 Three-Point loading test of wrapped beams (constant 68°F, 3.5 years)

(fabric rupture and debonding)

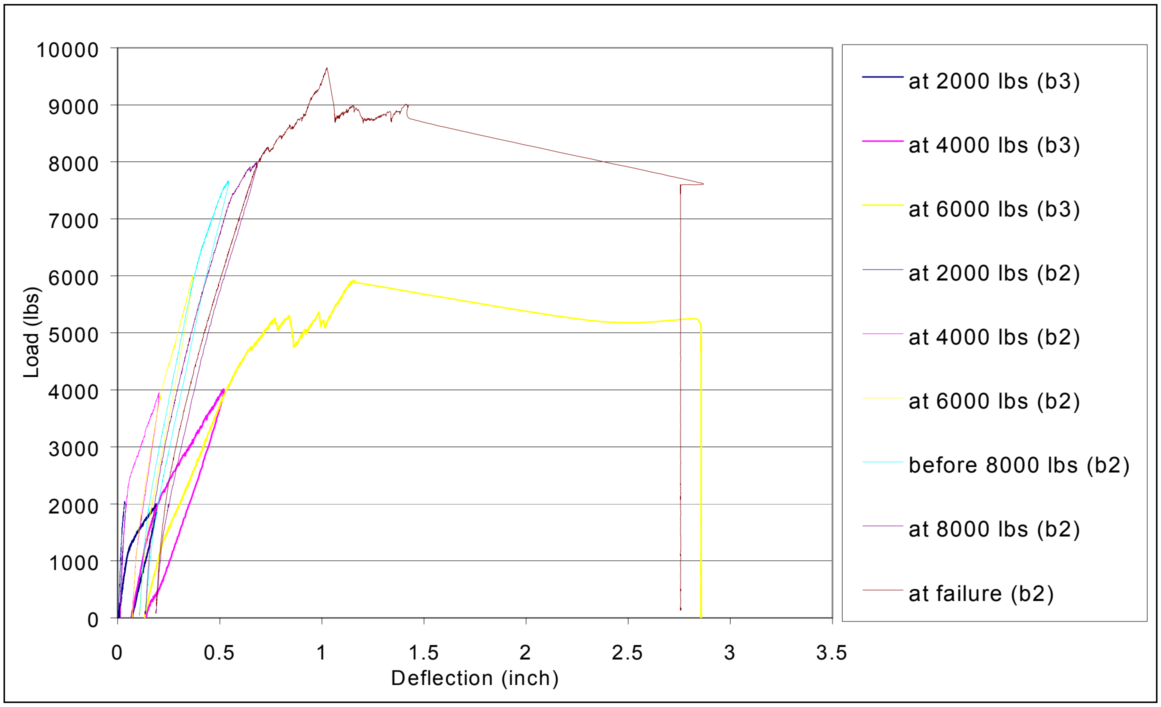

Fig 6.3 Deflection comparison in beam 2 (b2-3 wrap) and beam 3 (b3-1 wrap) tested in several loading/unloading cycles

6.3.1 Load (moment) capacity

Maximum load carried by concrete beams wrapped with one-layer of longitudinal carbon sheet was slightly higher than the theoretical value. This value of beams wrapped with three-layers of carbon sheets was slightly lower than the theoretical value. Maximum load ratios of those beams are between 0.963 and 1.12 in Table 6-2.

Table 6-2 Maximum (Exptl/Theor) load/moment ratio for wrapped beams under natural aging at constant 68°F

Beam	No. of longitudinal layers	Age (years)	Wrap* Type	Max load (Exptl.) (kips)	Max moment (Exptl.) (kip-ft)	Max load (Theor.) (kips)	Max load ratio (Exptl./Theor)
b1	1	3.5	B	6.25	10.94	5580	1.12
b2	3	3.5	B	9.65	16.89	10025	0.963
b3	1	3.5	B	5.91	10.35	5580	1.06

Note *b: one longitudinal layer of carbon fiber wrap at the beam bottom
Test span for three-point bending = 84 inch

6.3.2 Deflection

Deflections are expected to reduce due to wrapping. Deflection on beam (b2) wrapped with three-layers of longitudinal carbon fabric were on an average 50% less per kip (1000 lbs) of loading, as compared to beam (b3) with only one layer of longitudinal carbon fabric as shown in Table 6-3. This reduction in deflection depends upon the size of the beam, existing amount of internal reinforcement and number of FRP layers up to a certain thickness.

Table 6-3 Deflection comparison in beams with different number of fabrics at different load levels

Load level	Beam 2 (b2- three layers of fabric)		Beam 3 (b3- one layer of fabric)	
	Total Deflections (in.)	% Increase in deflection/kip	Total Deflections (in.)	% Increase in deflection/kip
At 2000 lbs	0.2348	-	0.3049	-
At 3000 lbs	0.2854	21.55	0.4190	37.42
At 4000 lbs	0.3496	22.49	0.5322	27.02
At 5000 lbs	0.4223	20.80	0.7153	34.40
		Avg. 21.6 %		Avg. 33%

6.3.3 Deformability factor

Deformability factors of beams wrapped with carbon sheet under room temperature of 68 °F for 3.5 years were 14.76 for beam b3 (1-layer) and 11.64 for beam b2 (3-layers) as shown in Table 6-4. It should be noted that the beam with three-layers results decreased in deflection and crack-width thus providing increased loads at which point the limiting values of deflection, crack-width, and curvature are reached. Thus, increased energy absorption at limiting curvature, i.e., denominator term, gives an apparent lower deformability factor.

Table 6-4 Maximum (Exptl/Theor) load ratio and deformability factors of wrapped beams aged at constant of 68 °F

Beam	No. of longitudinal layers	Wrap* Type	Max load (Exptl.) (kips)	Max moment (Exptl.) (kips)	Max load (Exptl.) (kips)	Max load ratio (Exptl/Theor)	Deformability (A_u/A_e)
b1	1	b	6.25	10.94	5.58	1.12	-
b2	3	b	9.65	16.89	10.03	0.963	11.64
b3	1	b	5.91	10.35	5.58	1.06	14.76

Note: *b: one longitudinal layer of carbon fiber wrap at the beam bottom
Test span for three-point bending = 84 inch

6.4 RESULTS AND ANALYSIS OF CFRP STRIPS EXTRACTED FROM BEAMS AT CONSTANT 68°F FOR 3.5 YEARS

The carbon fiber sheets were extracted from wrapped beams aged at constant 68°F (refer to section 6.3) after three-point bending test. The carbon fiber strips used for specimen preparation were selected such that any visible damaged or ruptured sections were avoided. The results in terms of fabric tensile strength and stiffness are presented in Table 6-5.

Table 6-5 Tension test results from CFRP strips extracted from beams at 68°F

Age (years)	Type	Sample	Maximum load (kips)	Average Max load (kips)	Stiffness (Msi)
0	Non-aged strips	1	1.800	1.905	33.3
		2	1.850		
		3	2.120		
		4	1.850		
3.5	From Aged beam	1	1.750	1.703	31.1
		2	1.730		
		3	1.630		
		4	1.700		

6.4.1 Tensile strength and stiffness of CFRP strips

Tensile strength and stiffness of CFRP strips from wrapped beams aged 3.5 years at constant 68°F were compared with these values of unaged specimens. Aged strips showed an average strength reduction of 10.6 % and stiffness reduction of 7.4 % (Table 6-6). However, it should be noted that the strips might contain micro damage, which could not be identified through visual examination, hence not accounted for in stress and stiffness reduction.

Table 6-6 Average tensile strength and stiffness and reduction for CFRP strips extracted from beams aged under constant 68°F

Specimen	Tensile strength and stiffness				% reduction in strength (average)	% reduction in stiffness (average)
	From aged beam		Unaged Specimen			
	Strength (kips.)	Stiffness (Msi)	Strength (kips.)	Stiffness (Msi)		
1	1.750	31.05 (Avg.)	1.800	33.33 (Avg.)	10.6%	7.4%
2	1.730		1.850			
3	1.630		2.120			
4	1.700		1.850			
	1.703 (Avg.)	31.05 (Avg.)	1.905 (Avg.)	33.33 (Avg.)		

6.5 RESULTS AND ANALYSIS OF BEAMS UNDER OUTSIDE WEATHERING FOR 3 YEARS

Results from beams of 6”× 15”×120” and wrapped with one longitudinal layer at the bottom of the beam aged naturally for 3 years are presented in terms of maximum failure load and moment in Table 6-7.

Table 6-7 Four-point bending test results for beams aged under outside weathering

Age (years)	Temp (F)	Beam	Wrap* Length (ft)	Max load (recorded) (kips)	Max. Moment (recorded) (Kip-ft)
3	Natural weathering	NA1	3	17.38	30.4
		NA2	4	-	-
		NA3	5	15.83	27.7

Note : * one longitudinal layer of carbon fiber wrap at the beam bottom
: Carbon fabrics were symmetrically bonded on either side of the centerline at beam bottom.
: shear span 3.5 ft

Load versus deflection values of wrapped concrete beams up to 8000 lbs after natural aging are presented in Figs 6.4 to 6.5. These beams were tested in three-cycles of loading and unloading before aging. During each year of natural aging, the beams were brought back into the laboratory and tested to evaluate mid span-deflections up to 8000 lbs. These deflections values are presented in Tables 6-8 and 6-9.

Table 6-8 Deflection of beams before natural (outside weathering) aging

Beams	Deflection (before aging in 3rd cycle) (in)	Residual Deflection (before aging in 2nd cycle) (in)	Total deflection (before aging in 3rd cycle) (in)
NA-1	0.1327	0.0569	0.1896
NA-2	0.1129	0.0456	0.1585
NA-3	0.1111	0.0516	0.1627

Table 6-9 Deflection of beams after natural (outside weathering) aging

Beams	Deflection (before aging in 3rd cycle) (in)	Deflection (after14 months of natural aging) (in)	Deflection (after 24 months of natural aging) (in)	Deflection (after 36months of natural aging) (in)
NA-1	0.1327	0.1327	0.1396	0.1494
NA-2	0.1129	0.1171	-	-
NA-3	0.1111	0.1134	0.1573	0.1406

Fig 6.4 Four-point loading for beams under natural weathering for 3 years

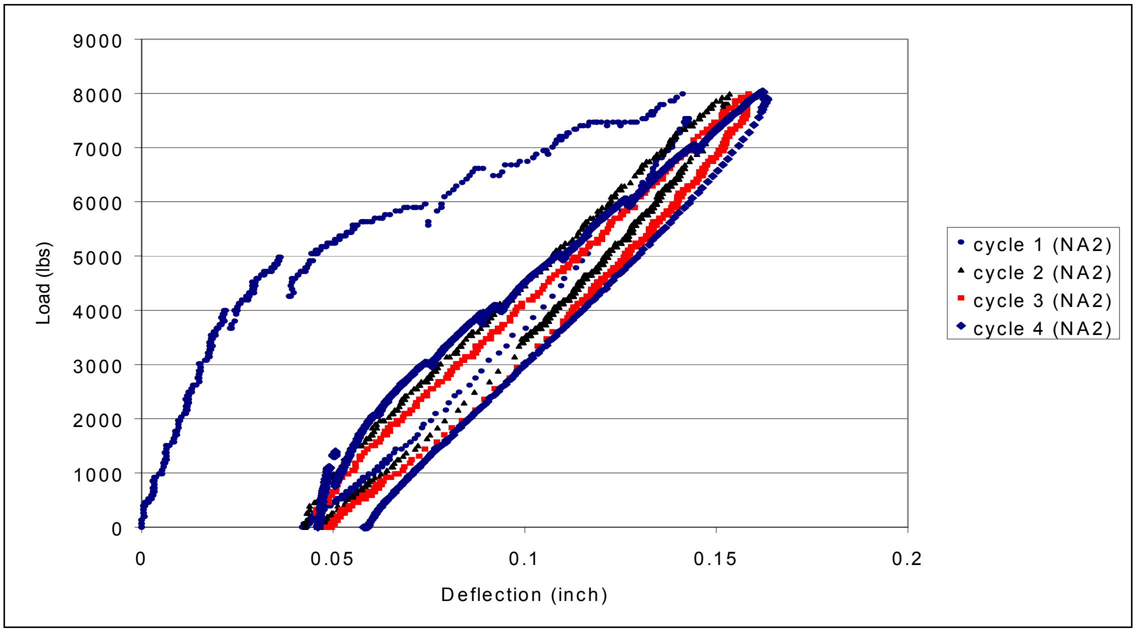

Fig 6.5 Load-deflection curve for beam NA 2 before (cycles 1, 2, 3) and after (cycle 4) natural aging of one year

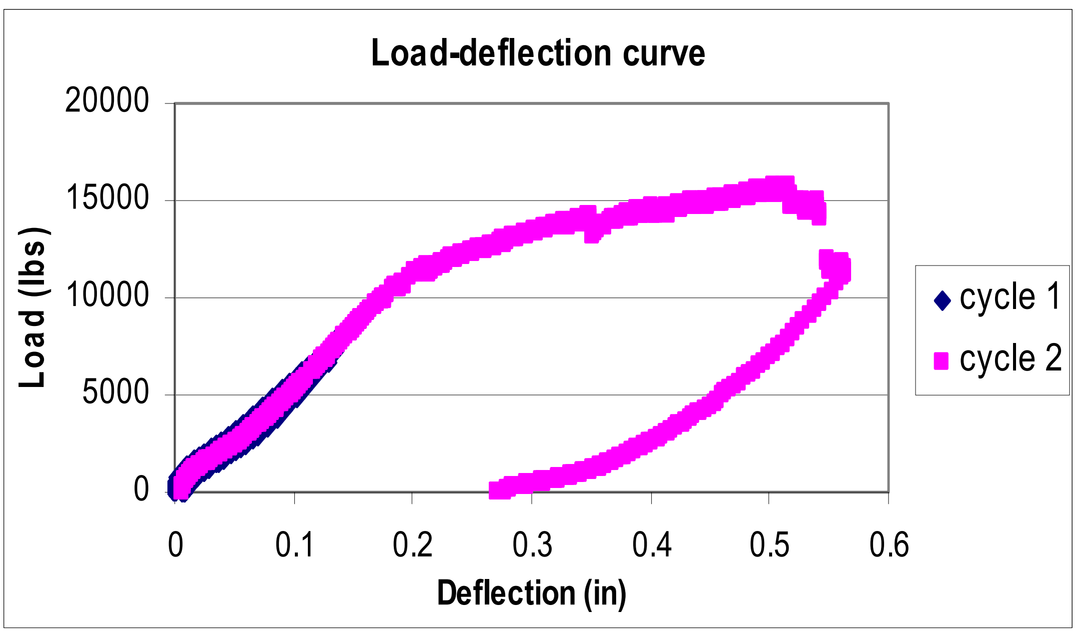

Fig 6.6 Load-deflection curve for beam NA-3 under natural aging for 3 years

6.5.1 Load (moment) capacity ratio, deformability and stiffness

Maximum loads carried by beams under natural weathering were higher than theoretical values except for beam NA2 that was tested to failure at 14 months. Deformability factors of beams NA1 and NA3 were 10.33 and 11.63, respectively, as shown in Table 6-10.The stiffness of beam NA-1 gradually decreased from 0% in first year to 12.3% in third year. Beam NA 2 failed in testing at 14 months hence the stiffness of this beam is presented for first year only. For beam NA-3, the stiffness reduction in the first year was 2.07%. But stress reductions in the second years were 41.6%, which was not consistent with 26.6% reduction observed during third year (Table 6-10). Due to the inconsistency, second year stiffness reductions for beam NA-3 is disregarded. Hence, it is important to use U-wraps to minimize bond line related degradation and corrosion of internal reinforcement.

The maximum increase in deflection of the beam aged naturally was 26.6 %, after 3 years. Beam stiffness reduction of 26.6% over three years is very high compared to 6.45% reduction in strength and 4.99% reduction in stiffness of the attached wraps. This reduction is attributed to several factors such as: bond line degradation at the CFRP-concrete interface, corrosion of internal steel reinforcement and handling stress.

Table 6-10 Maximum (Exptl./Theor) load ratio and deformability for wrapped beams under outside weathering

Beam	Age (years)	Wrap* length (ft)	Max load (Exptl.) (kips)	Max moment (Exptl.) (kip-ft)	Max load (Theor.) (kips)	Max moment (Theor.) (kip-ft)	Max load ratio (Exptl./Theor)	Deformability (A_u/A_e)
NA1	3	3	17.38	30.4	14.5	25.3	1.199	10.33
NA2	3	4	-	-	14.5	25.3	-	-
NA3	3	5	15.83	27.7	14.5	25.3	1.092	11.63

***Note** : one longitudinal layer of carbon fiber wrap at the beam bottom
: Carbon fabrics were symmetrically bonded on either side of the centerline at beam bottom.
: shear span 3.5 ft

Table 6-11 Difference in overall beam stiffness due to natural aging (at 8000 lbs) for different beams

Beams	Deflection (before aging in 3 rd cycle) (inch)	Deflection (after 14 months of natural aging in 4th cycle) (inch)	Stiffness Reduction after1 year of natural aging (%)	Deflection (after 2 years of natural aging in 4th cycle) (inch)	Stiffness Reduction after2 year of natural aging (%)	Deflection (after 3 years of natural aging in 4th cycle) (inch)	Stiffness Reduction after3 year of natural aging (%)
NA-1	0.1327	0.1327	-	0.1396	5.2	0.1494	12.3
NA-2	0.1129	0.1171	3.72	Failure at 14 months	-	-	-
NA-3	0.1111	0.1134	2.07	*	*	0.1406	26.6

* Deflection computations are disregarded due to inconsistence of the recorded value at the end of 2nd year.

6.6 RESULTS AND ANALYSIS OF CFRP STRIPS EXTRACTED FROM BEAMS UNDER OUTSIDE WEATHERING FOR 3 YEARS

The carbon fiber sheets were extracted from wrapped beams aged under outside weathering (refer to section 6.5) after three-point bending test. The carbon fiber strips used for specimen preparation were selected such that any damaged or ruptured sections were avoided. The results in terms of fabric tensile strength and stiffness are presented in Table 6-12.

Table 6-12 Tension test results from CFRP strips extracted from beams under outside weathering

Age (months)	Type	Sample	Maximum load (kips)	Average Max load (kips)	Stiffness (Msi)
3	outside	S1	1550	1.510	31.8
		S2	1480		
		S3	1550		
36	outside	NA1/1	1.450	1.433	30.3
		NA1/2	1.450		
		NA1/3	1.400		
	outside	NA3/1	1.450	1.467	30.7
		NA3/2	1.500		
		NA3/3	1.450		

6.6.1 Tensile strength and stiffness of CFRP strips

Average tensile strength and stiffness of strips extracted from beams under natural weathering for 3 years are between 1.433-1.467 kips and between 30.3-30.7 Msi, respectively.

Table 6-13 Average tensile strength and stiffness and reduction for CFRP strip

Specimen	Aging duration (months)	Tensile strength and stiffness			
		From aged beam		Reduction *(compared to 0 months)	
		Strength (kips)	Stiffness (Msi)	strength (%)	stiffness (%)
S	3	1.510	31.8	2.65	0.935
Avg.		Above values are already averaged.			
NA1	36	1.433	30.0	5.35	5.61
NA3		1.467	30.7	7.55	4.36
Avg. (Na1 and Na3)		1.450	30.4	6.45	4.99

Note: *Strength from 0 month carbon fiber strips = 1.550 kips
*Stiffness from 0 month carbon fiber strips= 32.1 Msi

Compared to unaged strips, maximum reduction in strength and stiffness of strips extracted from beams aged under outside weathering for 3 years was 7.55% and 5.61%, respectively.

6.7 STRUCTURAL RESPONSE FROM TEST DATA

6.7.1Natural aging of wrapped concrete beams at constant 68 °F for 3.5 years

Three-point loading tests were conducted on test beams aged naturally for 3.5 years (constant 68°F). CFRP strips were extracted from carbon fabrics of beams after aging and subsequent three-point bending tests on beams.

Load (moment) capacity

- Beams b1, b2, and b3 exhibited no significant variation in ultimate strength and stiffness behavior due to natural aging of 3.5 years with constant temperature.
- Experimental to theoretical ultimate load (moment) capacities of all the three naturally aged beams (b1, b2 and b3), varied from 1.04 to 1.12. (Table 6-2)
- At failure, strain values in carbon wraps bonded to concrete beams b1, b2 and b3 were found to be about 1.5% or higher indicating development of full tensile strength and bond between wrap and concrete, after 3.5 years of natural aging.

Deflection

- Average deflection per 1 kip of applied load was found to be about 50% less in beam b2 with three layers of carbon fabric as compared to beam b3 with one layer of carbon fabric, thus indicating the effectiveness of wrap in reducing deflections (Table 6-3). This reduction in deflection depends upon the size of the beam, existing amount of internal reinforcement and number of layers up to a certain thickness.

Deformability factor

- Deformability factors for beams b2 and b3 having three layers and one layer of carbon fabric, respectively were found to be 11.64 and 14.76, respectively. Additional deformation could be induced in the beam without catastrophic failure to attain higher deformability factor. However, additional deformations were not measured to establish final deformability factors (Table 6-4). It should be noted that the beam with three-layers resulted in decreased deflection and crack-width; thus providing increased loads at which the limiting values of deflection, crack-width, and curvature are reached. Thus, increased energy absorption at limiting curvature, i.e., denominator term, gives an apparent lower deformability factor.

Strength and stiffness of carbon fiber strips

- Tensile strength and stiffness of strips from wrapped beams aged for 3.5 years under room temperature of 68 °F showed an average strength and stiffness reduction of 10.6% and 7.4 %, respectively (Table 6- 6).

6.7.2 Natural aging of wrapped concrete beams under outside weathering for 3 years

Four-point loading tests were used to test beams aged under natural weathering for 3 years. During each year of natural aging, the beams were subjected to freezing and thawing during winter (snow) season, high and low temperature variation during summer, and temperature variation coupled with humidity variation during rainy season. After each aging period, the beams were brought back into the laboratory and the same four point loading tests were performed by loading them to 8,000 lbs (14 k-ft).

Load (moment) capacity

- Experimental to theoretical ultimate load (moment) capacities of the two naturally aged beams (NA1 and NA3) were 1.092 and 1.199, respectively (Table 6-10).
- Deformability factors of beams NA1 and NA3 were 10.33 and 11.63, respectively (Table 6-10).

Deflection

- There was no significant differences (less than 4 percent) in the deflection values of beams NA1, NA2 and NA3 (wrapped with carbon fabrics) after 14 months of natural aging.
- Stiffness reduction of 26.6% over three years is very high compared to 6.45% reduction in strength and 4.99% reduction in stiffness of the attached wraps. This reduction is attributed to several factors such as: bond line degradation at the CFRP-concrete interface, corrosion of internal steel reinforcement and handling stress. Therefore it is neglected from our overall analyses.

Strength and stiffness of CFRP strips

- Tensile strength and stiffness of CFRP strips extracted from wrapped beams aged for 3 years under natural weathering were compared with those values from non-aged specimens. Aged strips showed an average strength reduction of 6.45 % and stiffness reduction of 4.99 % (Table 6-13).

Chapter 7

CORRELATION OF AGING RESULTS

7.1 INTRODUCTION

Carbon fiber wraps undergo changes in properties due to aging. Aging can be physical or chemical (GangaRao, Vijay and Dutta, 1995). Chemical aging involves changes in the chemical or molecular structure of carbon fiber. Physical aging involves changes in the physical structure Degradation of mechanical properties depends upon: chemical and physical structure of the polymer (dislocation energy of primary, secondary bonds and other components of chemical structure such as steric factors, resonance stabilization), physical state of the material (morphology, orientation and sample size etc), contaminants, additives (lubricants, plasticizers and reinforcing fillers) modifiers, time and temperature, moisture, pressure, magnitude and nature of stress, environmental and biological factors.

7.2 AGING UNDER DIFFERENT ENVIRONMENT

Carbon wrapped beams and strips were conditioned under different schemes in chapter 5 and 6. Different conditioning schemes include:

- Water immersion aging at**:** room temperature, 110°F temperature and140°F temperature
- Alkaline (pH≈ 13) immersion aging at**:** room temperature and freeze-thaw conditions
- Salt (pH≈ 7) immersion aging at**:** room temperature and freeze-thaw conditions
- Natural aging at: constant 68°F of room temperature and outside weathering

- The strength and stiffness of carbon fiber strip aged under different conditions are shown in Figures 7.1 to 7.5. (It should be noted that most of the aged carbon fiber strip specimens were extracted from conditioned beams and then subjected to tension test.)

Aging schemes listed below show the impact of each conditioning method on strength reduction of CFRP strips in terms of highest to lowest effect.

1. Water immersion at 140 °F temperature
2. Alkaline immersion at room temperature
3. Salt immersion at room temperature
4. Alkaline immersion at freeze-thaw conditions
5. Salt immersion at freeze-thaw conditions
6. Water immersion at 110 °F temperature
7. Water immersion at room temperature
8. Natural aging at constant 68 °F of room temperature
9. Natural weathering (outside)

Aging schemes listed below show the impact of each conditioning method on stiffness reduction of CFRP strips in terms of highest to lowest effect.

1. Alkaline immersion at room temperature
2. Salt immersion at room temperature
3. Salt immersion at freeze-thaw conditions
4. Alkaline immersion at freeze-thaw conditions
5. Water immersion at 140 °F temperature
6. Water immersion at 110 °F temperature

7. Natural aging at constant 68 °F of room temperature

8. Natural weathering (outside)

9. Water immersion at 140 °F temperature

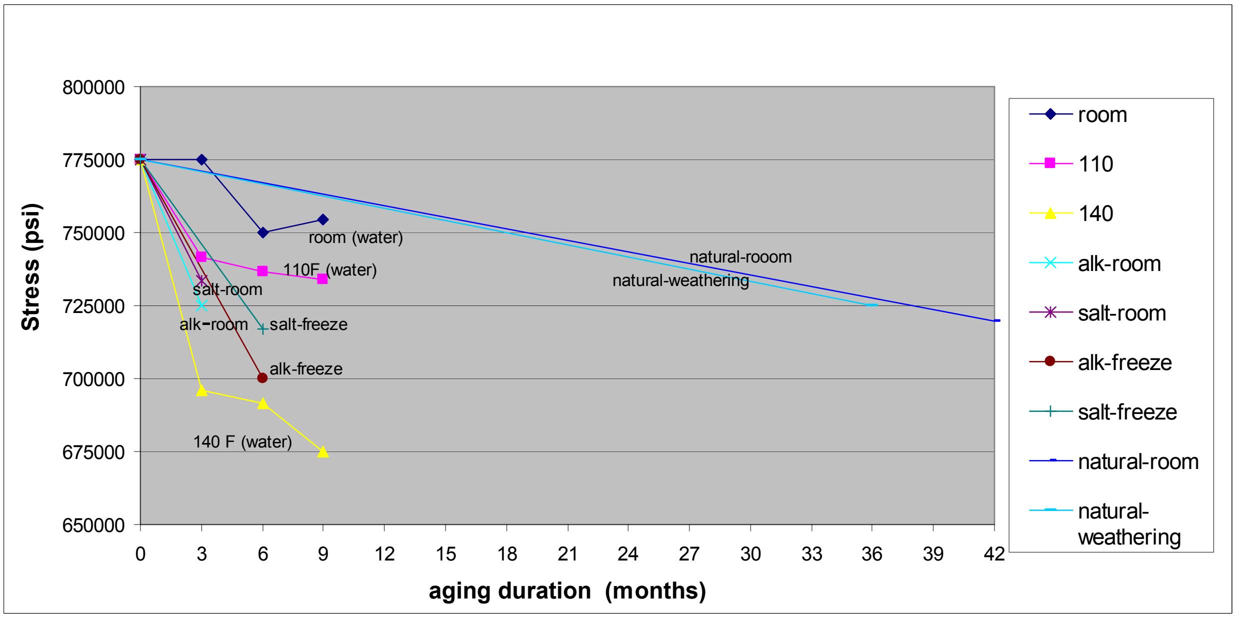

Fig 7.1 Tensile stress of CFRP strips with aging duration of 42 months

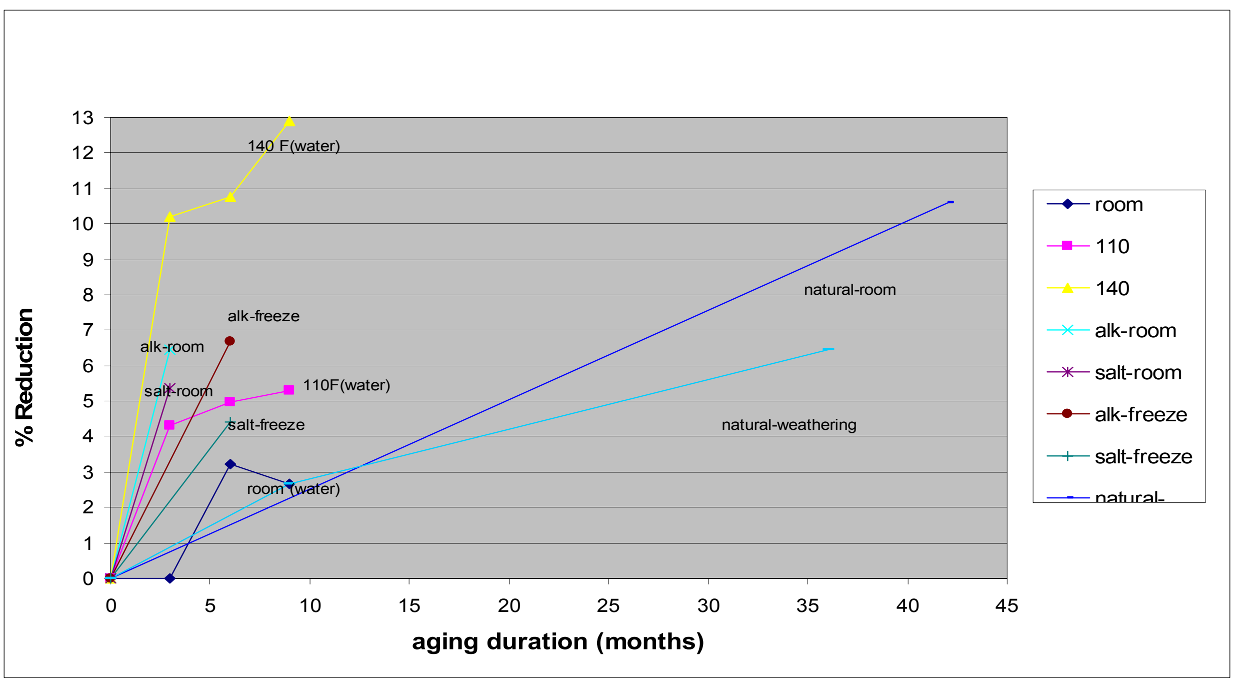

Fig 7.2 Tensile strength reduction of CFRP strips with aging duration of 42 months

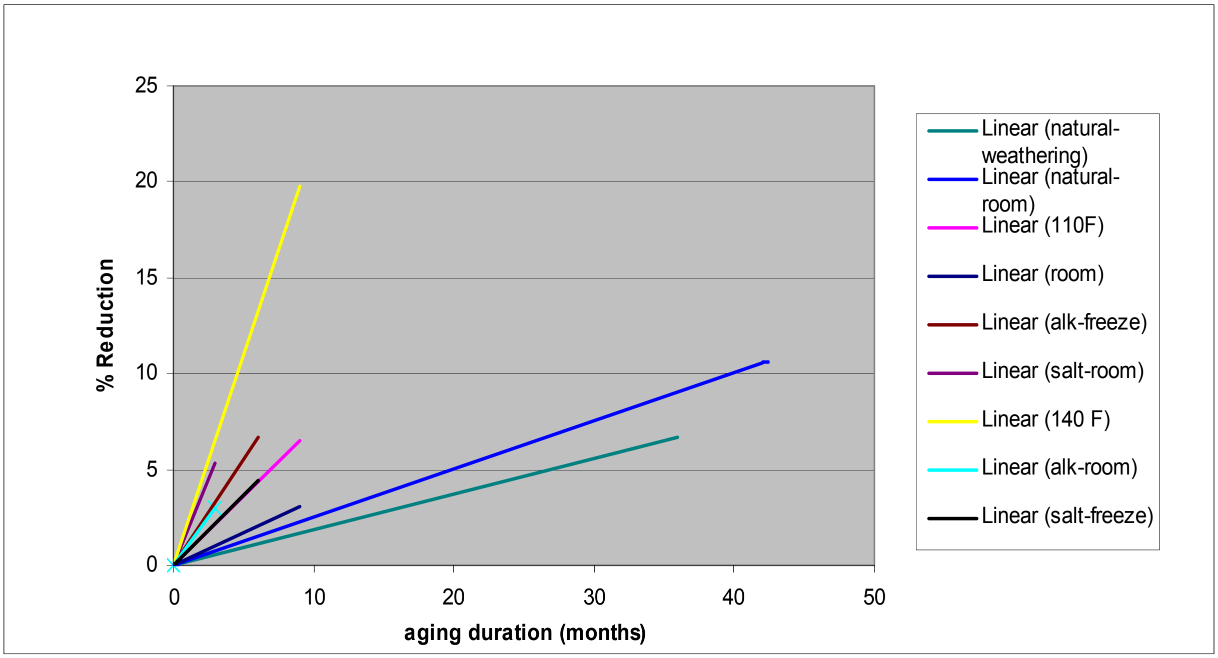

Fig 7.3 Tensile strength reduction of CFRP strips with aging duration of 42 months (best fit curve)

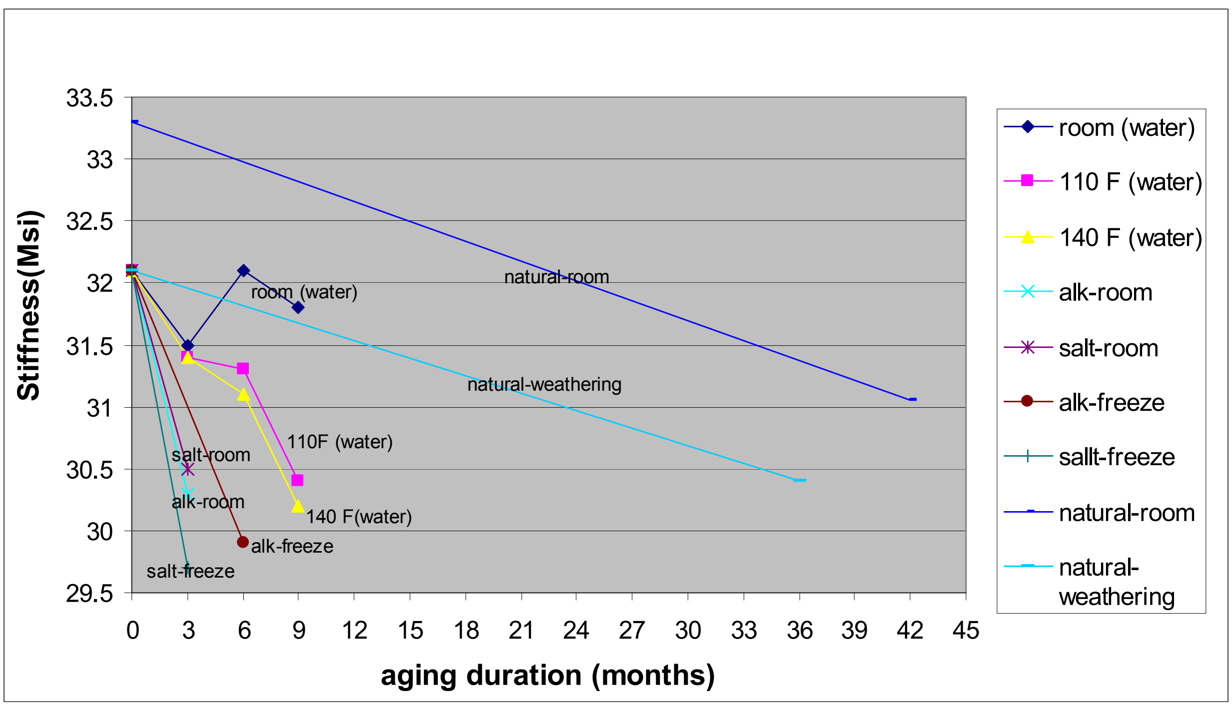

Fig 7.4 Tensile stiffness of CFRP strips with aging duration of 42 months

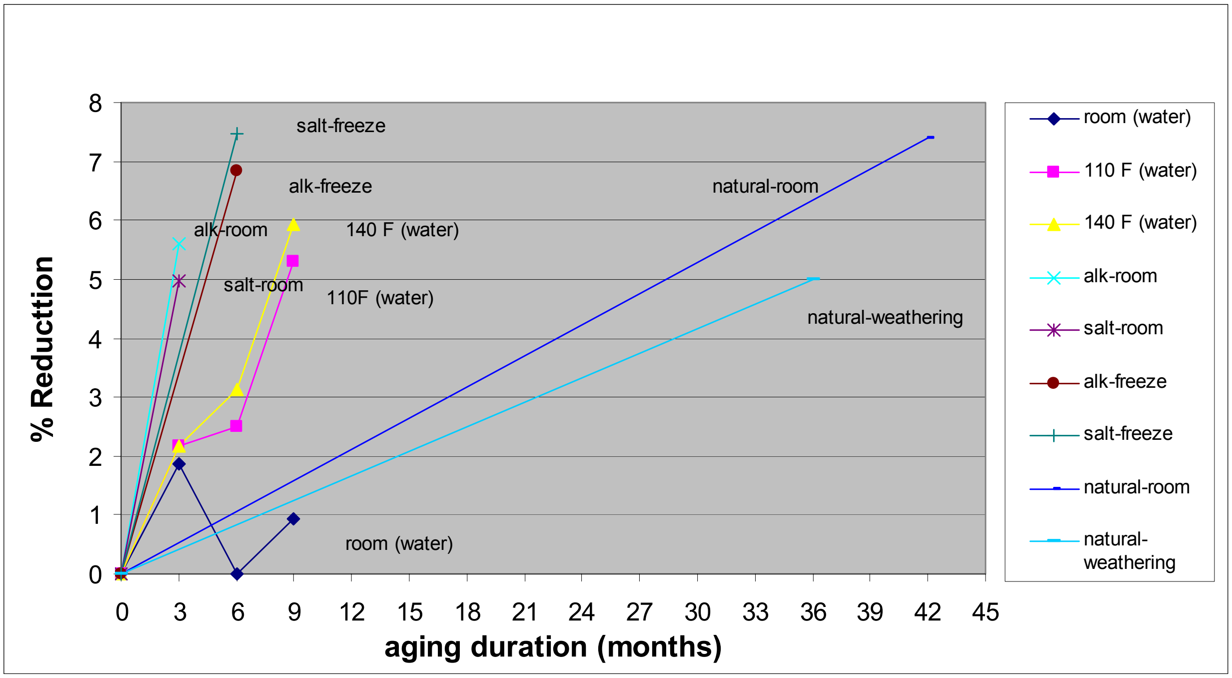

Fig 7.5 Tensile stiffness reduction of CFRP strips with aging duration of 42 months

7.3 CORRELATION OF ACCELERATED AND NATURAL AGING

Correlations of accelerated and natural aging have been carried out for GFRP composites by Litherland et al (1981). and Vijay and GangRao(1999). These correlations are basd on well proven time–temperature superposition theories commonly employed for aging analysis of polymers, whose results at one temperature can be used to predict the results at other temperatures by using time shift factors. This type of shift is simplified when the aging curves plotted on a semi-log scale and are parallel to each other.

Based on different conditioning schemes, which are still being continued at the CFC-WVU laboratories (Figure 7.6), two aging curves of CFRP wraps bonded to concrete and tested in tension are considered for correlation of accelerated and natural aging (Figure7.7). Nearly parallel curves in Figure 7.7 correspond to natural outside weathering and water immersion aging at 140°F temperature.

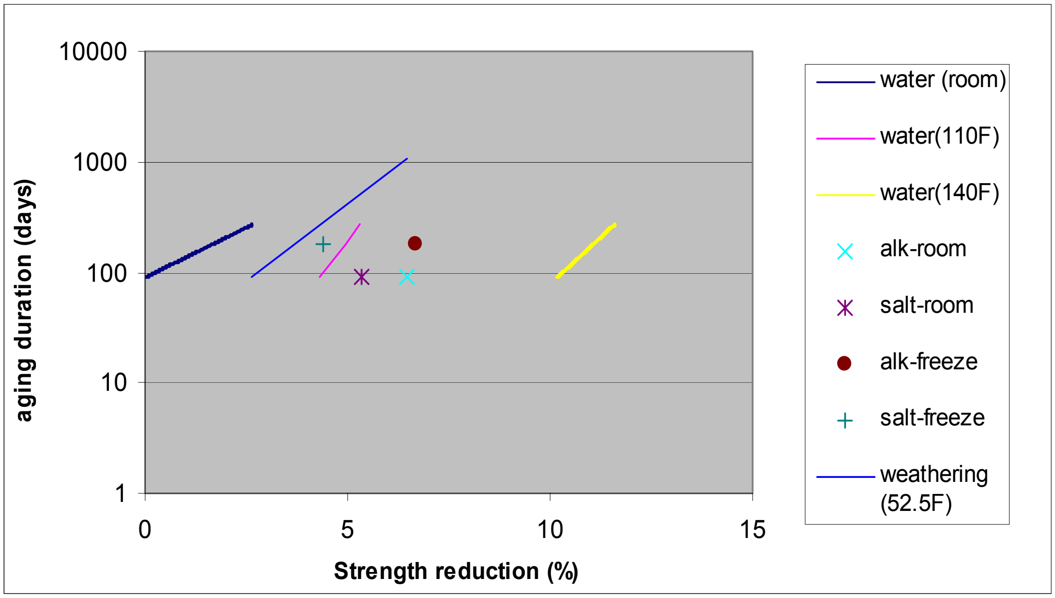

Fig 7.6 Strength reduction versus aging duration (from Figure 7.3)

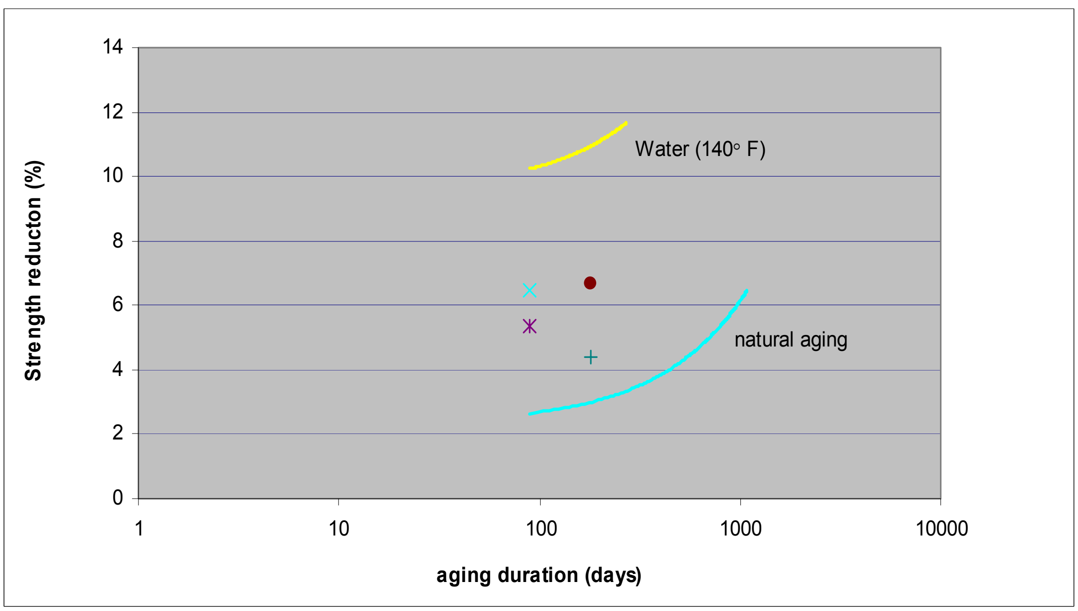

Fig 7.7 Strength reduction versus aging duration (from Figure 7.3)

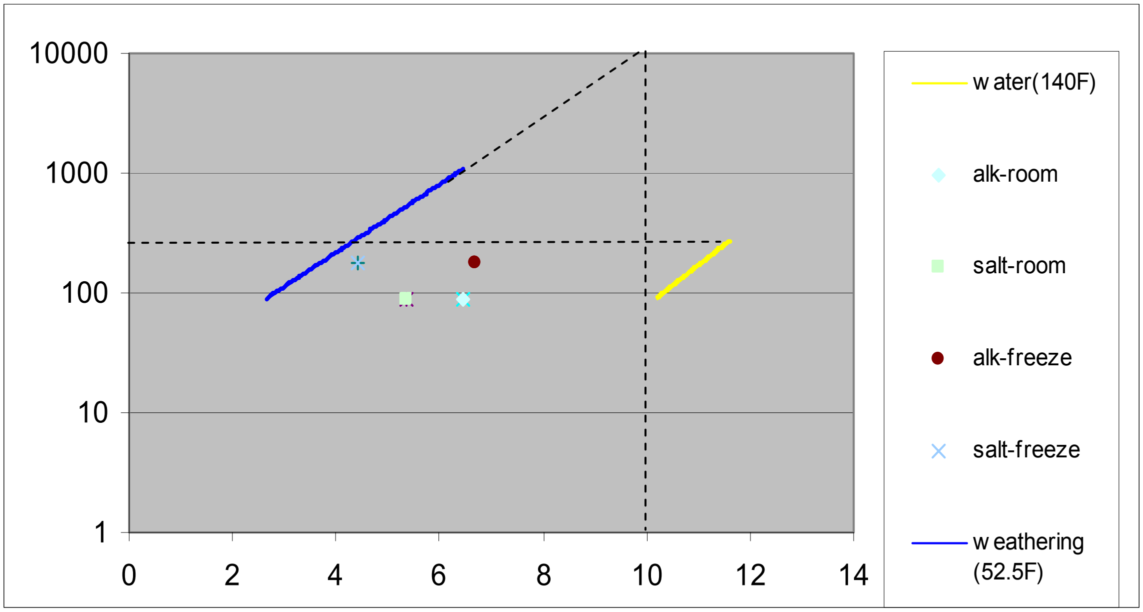

Fig 7.8 Strength reduction versus aging duration (from Figure 7.6)

From Figure 7.8

90 days of 140°F aging corresponds to 10% strength reduction

90 days of 140°F aging is equivalent to 10000 days of natural aging

Hence, 1 day of 140° F aging is equivalent to 111days of natural aging

Similarly, 270 days of 140° F aging corresponds to 12.9% strength reduction

270 days of 140° F aging is equivalent to 270×111= 29970 days of natural aging

270 days of 140° F aging is equivalent to 82 years of natural aging

Therefore, reduction factor of 0.85 imposed by ACI 440 for CFRP fabrics subjected to normal and aggressive outside exposure is conservatively justified because the test results indicate 12.9% reduction in 82 years. In our study, maximum strength reduction in CFRP strips aged naturally under atmospheric (outside) weathering was 6.5%. In another study, whose carbon/epoxy are being naturally aged under atmospheric weather near Miyakojima Island of Okinawa, Japan with a mean annual temperature of 73.4°F has shown only 3.4% reduction in strength (Petroleum Energy Center handout) as given in Figure 7.9. It should be noted that our results are based on CFRP strips extracted from wraps bonded to concrete beams (after beam aging and beam bending test).

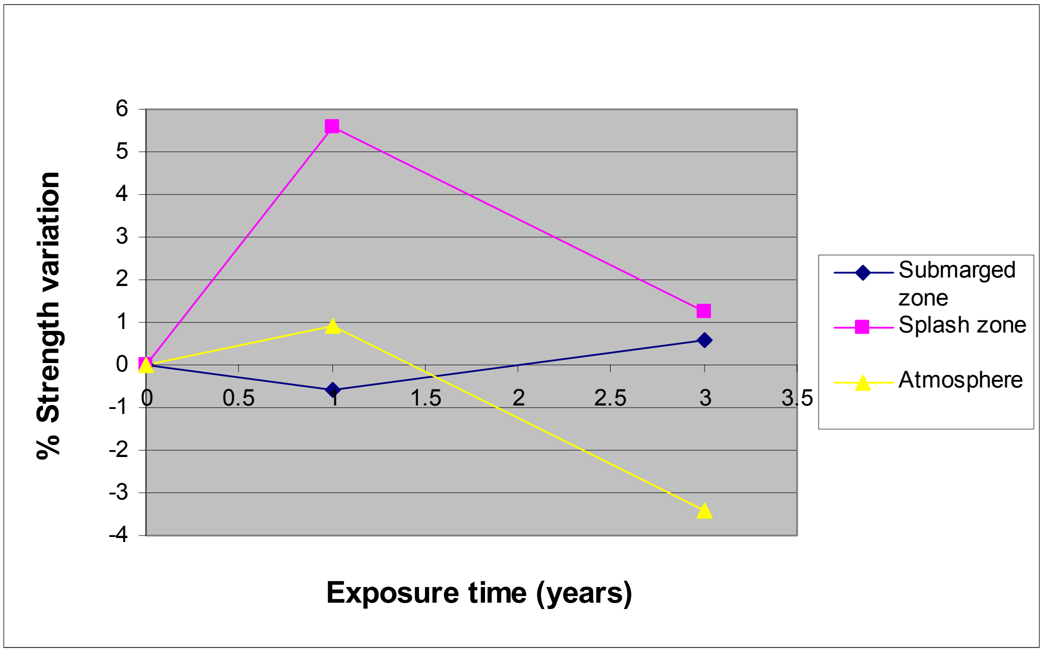

Fig 7.9 Strength variation of carbon fiber /Epoxy naturally aged at Miyakojima Islands (Ref: Petroleum Energy Center handout)

7.4 EFFEECT OF AGING ON TENSILE AND BOND STRENGTHS

Another part of this durability study conducted at CFC, WVU on the bond of CFRP and GFRP wraps with concrete indicates average variations in bond strength of specimens under accelerated aging to be less than 10% of unaged specimens. Accelerated aging consisted of parameters such as pH change (3 to 13), temperature fluctuations (room temperature and freeze-thaw conditions between (12°F-120°F) and varied degrees of sustained stress (0%-20%).

Bond strength reductions due to various types of aging by Barger (2000) were considered for comparison purposes. Between the two severe conditioning schemes of this study, i.e., water aging at 140 ^{0}F and alkaline aging at room and freeze thaw condition, the latter scheme was selected for comparison, because bond strength reductions due to water aging at elevated temperature were not a part of the study by Barger (2000).

Tests on CFRP bonded with concrete and conditioned in alkaline solutions under freeze thaw conditions for 6 months indicated a bond strength reduction of 7.3% (interpolated between 3 and 9 months data from Barger 2000), whereas tensile strength reduction was found to be 9.7% for similar aging scheme and duration of 6 months in this study (Table 5-45). Hence, bond strength reductions (9.7%) were higher than tensile strength reductions (7.3%) by about 33%.

Using the experimental and theoretical studies from Vijay and GangaRao (1999) and Barger (2000), 23% of maximum reduction in bond strength values was found in accelerated aging study. However, average bond strength reductions without sustained stress were found to be less than 10% in the study by Barger (2000).

It appears that bond strength would be more critical than the tensile strength of CFRP fabrics due to environmental exposure.

From the perspective of a structural designer, following conclusions are made:

1. Wrapping concrete beams with FRP fabrics improves the flexural strength and stiffness of the beam. Other methods such as shear enhancement are not within the scope of this study and not discussed.

2. Flexural strength and stiffness increase due to wrapping depend upon properties of the beam such as dimensions, f_c', existing properties and area of internal steel reinforcement and properties and area of external FRP reinforcement.

3. U-shaped wraps provide better energy absorption and durability as compared to one-sided bottom wrapping.

4. Deflections and crack-width are reduced due to wrapping.

5. Reduction factor of 0.85 imposed by ACI 440 for CFRP fabrics subjected to normal and aggressive outside exposure is conservatively justified because the test results indicate 12.9% reduction in 82 years.

7.5 SUMMARY

- In this research, maximum strength reduction in CFRP strips aged naturally under atmospheric (outside) weathering was 6.5 %. Research results of others indicated a CFRP/epoxy strength reduction of 3.5% over 3 years near Miyakojima Island of Okinawa, Japan. Strength reductions are typically higher during initial aging duration and then tend to reduce dramatically with time.
- Based on the correlation of accelerated aging to natural aging, 12.9 % strength reduction in carbon wraps bonded to concrete beams aged under 140°F for 9 months in our study is equivalent to 82 years
- Reduction factor of 0.85 imposed by ACI 440 for CFRP fabrics subjected to normal and aggressive outside exposure is conservatively justified because the test results indicate 12.9% reduction in 82 years.

Chapter 8

ANALYTICAL EVALUATION

8.1 INTRODUCTION

Carbon fiber sheet or fabric wrap is bonded to concrete beams to improve strength and stiffness of beams. Particularly, concrete beams wrapped with longitudinal carbon fiber sheets at bottom increase the maximum moment capacity.

In design, tension steel of concrete beams yield before failure of carbon fiber wraps. After the tension steel yield, it is possible to have both concrete compression failure or carbon fabric rupture. Other modes of failure are debonding between concrete and carbon sheet, creep, rupture etc. (Vijay et al., 1996). In addition, tensile stress-stain curve of carbon fiber sheet is linear up to failure. The following sections describe analytical evaluation of wrapped beams in terms of capacity and deflection computations. Examples shown in this chapter correspond to different beam specimens used in this research and actual properties of the reinforced concrete sections with CFRP wraps are utilized for computations.

8.2 BALANCED FAILURE

Balanced failure in wrapped beams is the condition when concrete and bottom carbon wraps reach predefined strain values. Generally, maximum strain value of carbon fiber sheet is defined as $\varepsilon_{car} = 0.012$. From theory, balanced failure is provided when ratio of depth between compression stress block to total beam is about 0.2. At this ratio, maximum concrete and carbon strain are 0.003 and 0.012, respectively, as shown in Table 8.1.

Table 8.1 Factors to compute the moment capacity

ε_{con}	ε_{car}	ϕ_t=(c/h)	ϕ_c =(c/h)	ϕ/2	$\eta=\varepsilon_{car}/\varepsilon_{car,max}$ $\varepsilon_{car,max}$ =0.012
0.003	0.012	0.2	0.2	0.100	1.00
0.003	0.011	-	0.214	0.107	0.92
0.003	0.010	-	0.231	0.115	0.83
0.003	0.009	-	0.250	0.125	0.75
0.003	0.008	-	0.273	0.136	0.67
0.003	0.007	-	0.300	0.150	0.58
0.003	0.006	-	0.333	0.167	0.50
0.003	0.005	-	0.375	0.188	0.42
0.003	0.004	-	0.429	0.214	0.33
0.003	0.003	-	0.500	0.250	0.25
0.003	0.002	-	0.600	0.300	0.17
0.003	0.001	-	0.750	0.375	0.08
0.003	0.000	-	1.000	0.500	0.00

Note ϕ = (c/h) = ε_{car} / (ε_{con} + ε_{car})
ϕ = (c/h) ratio
ε_{car} = Strain of carbon fiber sheet
ε_{con} = Strain of concrete

8.3 TENSION FAILURE

The tension failure for concrete beams wrapped with carbon sheets is different than the conventional reinforced concrete beams. In a tension failure, tension steel in a test beam yields before the carbon fiber strain reaches its maximum value, while concrete strain will be less than ultimate strain value.

8.4 COMPRESSION FAILURE

The compression failure in concrete beams wrapped with carbon sheet occurs mostly after the tension steel has yielded. In this case, concrete reaches its ultimate strain before carbon sheet strain reaches predefined maximum strain value.

8.5 ULTIMATE STRENGTH DESIGN

Behavior of concrete is considered non-linear in ultimate strength design. The equivalent rectangular stress block has a mean stress of 0.85 f_c' and a depth of 'a'.

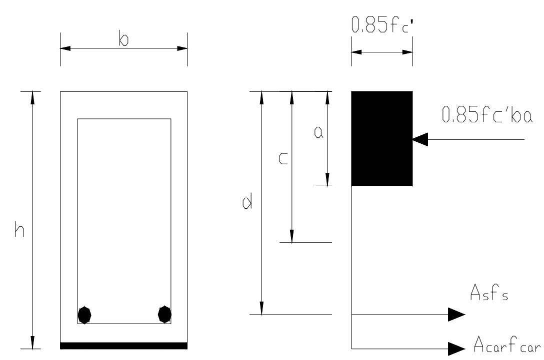

Fig 8.1 Force equilibrium in a wrapped concrete beam

Force equilibrium:

$$T_{steel} = A_s f_s \tag{8.1}$$

$$T_{car} = A_{car} f_{car} \tag{8.2}$$

$$C_{con} = 0.85 f_c' ab \tag{8.3}$$

Tensile force(T) = Compressive force (C)

$$T_{steel} + T_{car} = C_{con} \tag{8.4}$$

$$A_s f_s + A_{car} f_{car} = 0.85 f_c' ab \tag{8.5}$$

Moment equilibrium:

$$M_n = A_s f_s (d - 0.5a) + A_{car} f_{car} (h - 0.5a) \tag{8.6}$$

Where f_c' = concrete ultimate stress

f_s = steel tensile stress

f_{car} = carbon tensile stress

A_s = area of tension steel reinforcement

A_{car} = area of carbon sheet

8.6 RESISTING MOMENT CALCULATION

Resisting moments of a wrapped beam can be calculated similar to conventional reinforced concrete beam theory. Several calculations are shown for various beams considered in this study with different number of CFRP layers.

8.6.1Resisting moment of one layer carbon fiber wrapped beam

Example 1

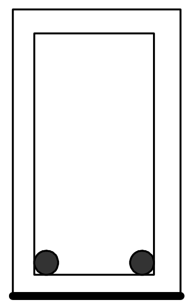

Fig 8.2 Carbon fiber wrapped beam cross section (1 longitudinal layer)

Dimension: b=5inch

h=8inch

d=6 inch

d'=2 inch

Reinforcement: Tension = 2#3 bars

Compression = Nominal

Shear = Adequate

Given: f'_c= 4 ksi

f_y = 60ksi

E_{car}= 33 Msi

A_s= 0.22 in2

A'_s= Neglible

$\varepsilon_{car,max}$=0.012

Solution: Determine whether the wrapped beam will fail in compression or tension failure by comparing ρ of the beam with balanced reinforcement condition ρ_b .

From equilibrium: compression = tension

$A_s f_y = 0.85 f_c' ab$

$\rho = (0.85\beta_1\ f_c' / f_y) \times (0.003 / (0.003 + \varepsilon_s))$

At balanced condition: $\varepsilon_s = 0.003$

$f'_c = 4$ ksi and $\beta_1 = 0.85$

$\rho_b = (0.85\times0.85\times4 /60) \times(0.003/ (0.003+0.00207)) = 0.0285$

Calculate ρ of beam:

$\rho = A_s / (bd) = 0.22/(5\times6) = 0.00733$

Commentary: Since ρ of the beam is significantly less than that required for balanced failure. Then, this beam can be assumed in tension failure.

From equilibrium: compression = tension

$$C_{concrete} = T_{steel} + T_{carbon}$$

$$0.85 f_c' ab = A_s f_s + A_{car} f_{car}$$

Assume Tension failure $f_s = f_y$, $f_{car} = f_{car,max}$ and $a = \beta_1\ c$

$0.85\times0.85\times4\times c\times5 = (0.22 \times 60) + [(0.004\times5\times 33000\times 0.003) \times ((8-c) /c)]$

$c = 1.505$ inch and $a = 1.279$ inch

Check for strain compatibility:

$$\varepsilon_s = 0.003\times(6.5-1.505)/1.505 = 0.00996$$

$$\varepsilon_s > \varepsilon_y \ (0.00207) \quad \text{then} \quad f_s = f_y$$

$$\varepsilon_{car} = 0.003\times(8-1.505)/1.505 = 0.1295$$

$$\varepsilon_{car} > \varepsilon_{car,max} \ (0.012) \quad \text{then} \quad f_{car} = f_{car,max}$$

Capacity of resisting moment for Carbon fiber wrapped beam

$$M_n = A_s f_y (d-0.5a) + A_{car} f_{car,max} (h-0.5a)$$

$$=[0.22\times60\times(6-(0.5\times1.279))] + [(0.004\times5\times500)\times(8-(0.5\times1.279))]$$

$$= 129 \text{ k-in} = 10.75 \text{ k-ft}$$

From three point bending test: span 50 inch

$$P_n = 4\, M_n / \text{span}$$

$$= 4 \times 129/50$$

$$= 10.32 \text{ kip}$$

Hence, Maximum load and resisting moment from theory are 10.32 kip and 10.75 kip-ft, respectively.

Carbon fiber wrapped concrete beam

Resisting moment of one layer carbon fiber wrapped beam

Example 2

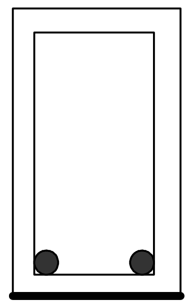

Fig 8.3 Carbon fiber wrapped beam cross section (1 longitudinal layer)

Dimension: b=6inch

h=15inch

d=13inch

d'=1.5inch

Reinforcement: Tension = 2#3 bars

Compression = Nominal

Shear = Adequate

Given: f'_c= 4 ksi

f_y = 60ksi

E_{car}= 33 Msi

A_s= 0.22 in2

A'_s= Neglible

$\varepsilon_{car,max}$=0.012

Solution: Determine whether the wrapped beam will fail in compression or tension failure by comparing ρ of the beam with balanced reinforcement condition ρ_b .

From equilibrium: compression = tension

$A_s f_y = 0.85 f_c' ab$

$\rho = (0.85 \beta_1 f_c' / f_y) \times (0.003 / (0.003 + \varepsilon_s))$

At balanced condition: $\varepsilon_s = 0.003$

$f'_c = 4$ ksi

$\beta_1 = 0.85$

$\rho_b = (0.85 \times 0.85 \times 4 /60) \times (0.003/ (0.003+0.00207))$

$\rho_b = 0.0285$

Calculate ρ of beam:

$\rho = A_s / (bd) = 0.22/(5 \times 13) = 0.00338$

Commentary: Since ρ of the beam is significantly less than that required for balanced failure. Then, this beam can be assumed in tension failure.

From equilibrium: compression = tension

$$C_{concrete} = T_{steel} + T_{carbon}$$

$$0.85 f_c' ab = A_s f_s + A_{car} f_{car}$$

Assume Tension failure $f_s = f_y$, $f_{car} = f_{car,max}$ and $a = \beta_1 c$

$0.85 \times 0.85 \times 4 \times c \times 6 = (0.22 \times 60) + [(0.004 \times 5 \times 33000 \times 0.003) \times ((13-c) /c)]$

$c = 1.584$ inch and $a = 1.346$ inch

Check for strain compatibility:

$\varepsilon_s = 0.003\times(13-1.584)/1.584 = 0.0216$

$\varepsilon_s > \varepsilon_y$ (0.00207) then $f_s=f_y$

$\varepsilon_{car} = 0.003\times(15-1.584)/1.584 = 0.0254$

$\varepsilon_{car} < \varepsilon_{car,max}$ (0.012)

Capacity of resisting moment for Carbon fiber wrapped beam

$M_n = A_s f_y(d-0.5a) + A_{car} f_{car,max} (h-0.5a)$

$=[\ 0.22\times60\times(13-(0.5\times1.584))]\ +[\ (0.004\times5\times500)\times$

$(15-(0.5\times1.560))]$

$= 303$ k-in $= 25.3$ k-ft

From four point bending test: shear span 3.5 ft

$P_n = 2\ M_n /$ span

$= 2\times25.3/3.5$

$= 14.5$ kips

Hence, Maximum load and resisting moment from theory are 14.5 kips and 25.3 kip-ft, respectively.

Carbon fiber wrapped concrete beam

8.6.2Compute resisting moment of two layer carbon fiber wrapped concrete beam

Example 3

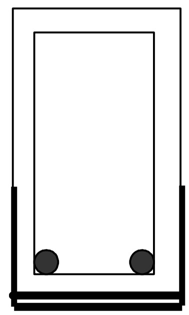

Fig 8.4 Carbon fiber wrapped beams cross section (2 longitudinal layers)

Dimension: b=5inch

h=8inch

d=6.5inch

d'=1.5inch

Reinforcement: Tension = 2#3 bars

Compression = Nominal

Shear = Adequate

Given: f'_c= 4 ksi

f_y = 60ksi

E_{car}= 33 Msi

A_s= 0.22 in2

A'_s= Neglible

$\varepsilon_{car,max}$=0.012

Solution: Determine whether the wrapped beam will fail in compression or tension failure by comparing ρ of the beam with balanced reinforcement condition ρ_b .

From equilibrium: compression = tension

$A_s f_y = 0.85 f_c' ab$

$\rho = (0.85\beta_1 f_c' / f_y) \times (0.003 / (0.003 + \varepsilon_s))$

At balanced condition: $\varepsilon_s = 0.003$

$f'_c = 4$ ksi

$\beta_1 = 0.85$

$\rho_b = (0.85 \times 0.85 \times 4 / 60) \times (0.003 / (0.003 + 0.00207))$

$\rho_b = 0.0285$

Calculate ρ of beam:

$\rho = A_s / (bd) = 0.22 / (5 \times 6.5) = 0.00677$

Commentary: Since ρ of the beam is significantly less than that required for balanced failure. Then, this beam can be assumed in tension failure.

From equilibrium: compression = tension

$$C_{concrete} = T_{steel} + T_{carbon}$$

$$0.85 f_c' ab = A_s f_s + A_{car} f_{car}$$

Assume Tension failure $f_s = f_y$, $f_{car} = f_{car,max}$ and $a = \beta_1 c$

$0.85 \times 0.85 \times 4 \times c \times 5 = (0.22 \times 60) + [(0.008 \times 5 \times 33000 \times 0.003) \times ((8 - c)/c)]$

$c = 1.835$ inch and $a = 1.560$ inch

Check for strain compatibility:

$$\varepsilon_s = 0.003\times(6.5-1.835)/1.835 = 0.00763$$

$$\varepsilon_s > \varepsilon_y \ (0.00207) \qquad \text{then} \qquad f_s=f_y$$

$$\varepsilon_{car} = 0.003\times(8-1.835)/1.835 = 0.01008$$

$$\varepsilon_{car} < \varepsilon_{car,max} \ (0.012)$$

Capacity of resisting moment for Carbon fiber wrapped beam

$$M_n = A_s f_y(d-0.5a) + A_{car} f_{car,max}(h-0.5a)$$

$$=[0.22\times60\times(6.5-(0.5\times1.560))]+[(0.008\times5\times33000\times0.01008)\times(8-(0.5\times1.560))]$$

$$= 172 \text{ k-in} = 14.33 \text{ k-ft}$$

From three point bending test: span 50 inch

$$P_n = 4\ M_n / \text{span}$$

$$= 4 \times 172/50$$

$$= 13.76 \text{ kips}$$

Hence, Maximum load and resisting moment from theory are 13.76 kip and 14.33 kip-ft, respectively.

8.7 DEFLECTION CALCULATION

Compute deflection of concrete beam with one layer carbon fiber wrap with following details:

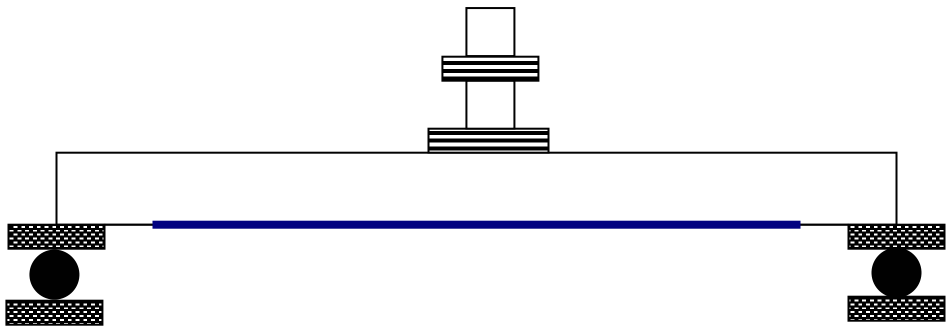

Fig 8.5 Carbon fiber wrapped beam (1 longitudinal layer)

Dimension: b=5inch

h=8inch

d=6 inch

d'=2inch

Reinforcement: Tension = 2#3 bars

Compression = Nominal

Shear = Adequate

Given: f'_c= 4 ksi

f_y = 60ksi

E_{car}= 33 Msi

A_s= 0.22 in2

A'_s= Neglible

$\varepsilon_{car,max}$=0.012

Solution

$n_s \;\; = E_s/E_c = \;29\text{Msi}/ (57000 \times (4000^{0.5})\text{ psi} = 8$

$n_{car} = E_{car}/E_c= 33\text{Msi}/ (57000 \times (4000^{0.5})\text{ psi} = 9$

$A_{concrete}$ from steel area = $n_sA_s = 8\times0.22 = 1.76\text{in}^2$

$A_{concrete}$ from carbon fiber area = $n_{car}\ A_{car} = 5\times0.004\times9 = 0.18\text{ in}^2$

$I_g = bh^3/12= (5\times8^3)/12 = 213\text{ in}^4$

For the transformed cracked section
Find the neutral axis position

$5x^2/2= 1.76(6 -x) +0.18(8-x)$

$2.5\ x^2 +1.94x -12 = 0$

$x = 1.837$ inch

Find moment of inertia of crack section

$I_{cr}= bx^3/3 + n_sA_s(d-x)^2+n_{car}A_{car}(h-x)^2$

$= (5\times1.915^3)/3 + 1.76(6 -1.915)^2 + 0.18(8-1.915)^2$

$= 47.4$ inch

Find cracking moment

$f_r \;\; = 7.5f\text{'}c0.5 = 7.5(4000)0.5 = 474\text{ psi}$

$M_{cr} = f_rI_g/y_t = 474(213)/4 = 2.10\text{ k-ft}$

Three-point bending test
Find deflection of one –layer carbon fiber wrapped beam

$(\Delta_i)_t = \;\; (\Delta_i)_{DL} + (\Delta_i)_{LL}$

$= [5wL^3/(384EI_e)] + [PL^3/(48EI_e)]$

Calculation of different parameters is given in Table 8-2.

Table 8-2 Load-deflection from theory

Load (kips)	M_{max} (k-ft)	M_{cr}/M_{max}	$(M_{cr}/M_{max})^3$	I_e (in^4)	Deflection		
					Dead load	Live Load	total
0	0	0	0	47.4	0.000687	0	0.000687
1	1.04175	2.015839	8.191574	1403.925	0.000687	0.00089	0.001578
2	2.0835	1.007919	1.023947	216.9656	0.000687	0.011523	0.01221
3	3.12525	0.671946	0.303392	97.64165	0.000687	0.038406	0.039093
4	4.167	0.50396	0.127993	68.5957	0.000687	0.072891	0.073578
5	5.20875	0.403168	0.065533	58.2522	0.000687	0.107292	0.107979
6	6.2505	0.335973	0.037924	53.68021	0.000687	0.139716	0.140404
7	7.29225	0.287977	0.023882	51.35488	0.000687	0.170383	0.17107
8	8.334	0.25198	0.015999	50.04946	0.000687	0.199802	0.20049
9	9.37575	0.223982	0.011237	49.2608	0.000687	0.228376	0.229064
10	10.4175	0.201584	0.008192	48.75652	0.000687	0.256376	0.257063
11	11.45925	0.183258	0.006154	48.41918	0.000687	0.283978	0.284666
12	12.501	0.167987	0.00474	48.18503	0.000687	0.3113	0.311987

Note: M_{max}= applied moment

M_{cr} = Cracking moment

I_e = Effective moment of inertia

Chapter 9

CONCLUSIONS AND RECOMMENDATION

9.1 INTRODUCTION

Carbon fiber wrapped beams were tested after aging them in water at room, 110°F and 140°F temperature. Wrapped beams were also aged in alkaline and salt solution at room and freeze-thaw conditions. In addition, wrapped beams were aged naturally at constant room temperature of 68°F and weathered outside. Various parameters such as ultimate load (bending moment), deflection, crack-width and deformability factor were compared for different conditioning schemes. Tension tests were conducted on CFRP strips extracted from the aged beams after beam bending tests. Strength and stiffness variation of tension strips under accelerated aging were compared with those from natural aging. A total of 36 beams and 98 strips were tested under different aging conditions, including natural aging.

9.2 CONCLUSIONS FOR LOAD (MOMENT) CAPACITY

<u>Water immersion aging</u>

- Compared to room temperature, maximum reduction in experimental /theoretical load (moment) ratio was 9.68 % during 9 months of 140 °F aging.

<u>Alkaline and salt immersion aging at room temperature</u>

- Maximum load capacities of beams aged in alkaline solution were slightly lower than those aged in salt solution for both types of bottom and U-shaped carbon wrapping. U-shape wrapped beams performed better than those of bottom wrapped beams in terms of improved load capacity with the additional barrier it provides against moisture ingress. As compared to bottom wrapped beams, experimental to theoretical load ratio in U–shape wrapped beams were higher by 4.68 % and 6.60% for alkaline and salt conditioning, respectively.

<u>Alkaline and salt immersion aging under freeze-thaw conditioning</u>

- Average ratios of experimental to theoretical load (moment) capacity of most of the wrapped concrete beams aged in alkaline and salt solutions under freeze-thaw conditioning for 6 months varied between 1.042 and 1.305 (Table 5-39).
- Maximum load capacities of beams aged in alkaline solution are slightly lower than those for beams aged in salt solutions for both types of bottom and U-shaped wrapping.

<u>Natural aging at constant 68 °F of room temperature</u>

- Beams b1, b2, and b3 exhibited no significant variation in ultimate strength and stiffness behavior due to natural aging of 3.5 years with constant temperature. Experimental to theoretical ultimate load (moment) capacities of all the three naturally aged beams (b1, b2 and b3) varied from 1.04 to 1.12.

<u>Natural aging (outside weathering)</u>

- Experimental to theoretical ultimate load (moment) capacities of the two naturally aged beams (NA1 and NA3) were 1.092 and 1.199, respectively.

Overall, all the aged beams exhibited experimental/theoretical load (moment) ratios exceeding 1 (only one beam was an exception). Most severe aging scheme was found to be water aging at 140 ^{0}F, which resulted in a reduction of 9.68% in maximum experimental/theoretical load (moment) ratio over 9 months. It should be noted that this reduction involves the effect of aging on all beam components including steel reinforcement, concrete and CFRP wrap.

9.3 CONCLUSIONS FOR DEFLECTION

Water immersion aging

- Maximum reduction in the ratio of load at limiting deflection (l/360, l/240 and l/180) to maximum load for water aging at room, 110 ^{0}F and 140 ^{0}F during 9 months was 7.29%, when compared to either room temperature or beams aged for 3 months.

Alkaline and salt immersion aging at room temperature

- Ratio of load at limiting deflection (l/360, l/240 and l/180) to maximum load was lower in alkaline solution by a maximum of 12.15% as compared to salt conditioning during 3 months of aging.

Alkaline and salt immersion aging under freeze-thaw conditioning

- Ratio of load at limiting deflection (l/360, l/240 and l/180) to maximum load was lower in alkaline solution by a maximum of 8.77% as compared to salt conditioning during 6 months of aging.

Natural aging at constant 68 °F of room temperature

- Average deflection per 1 kip of applied load was found to be about 50% less in beam b2 with three layers of carbon fabric as compared to beam b3 with one layer of carbon fabric, thus indicating the effectiveness of wrap in reducing deflections. This reduction in deflection depends upon the size of the beam, existing amount of internal reinforcement and number of FRP layers up to a certain thickness.

Natural aging (outside weathering)

- Beam stiffness reduction of 26.6% over three years is very high compared to 6.45% reduction in strength and 4.99% reduction in stiffness of the attached wraps. This reduction of 26.6% in beam is attributed to several factors such as: bond line degradation at the CFRP-concrete interface, corrosion of internal steel reinforcement and handling stress. Hence, it is eliminated from our aging analysis.

Overall, reductions in ratio of loads at limiting deflections to respective maximum loads due to aging were a maximum of 12.15%. It should be noted that this reduction involves the effect of aging on all beam components including steel reinforcement, concrete and CFRP wrap.

9.4 CONCLUSIONS FOR CRACK WIDTH

Water immersion aging

- Maximum reduction in the ratio of load at limiting crack-width (0.016”) to maximum load for water aging at room, 110 ^{0}F and 140 ^{0}F during 9 months was 7.98%, when compared to either room temperature or beams aged for 3 months.

Alkaline and salt immersion aging at room temperature

- Ratio of load at limiting crack-width (0.016”) to maximum load was lower in alkaline solution by a maximum of 6.07% as compared to salt conditioning during 3 months of aging.

Alkaline and salt immersion aging under freeze-thaw conditioning

- Ratio of load at limiting crack-width (0.016”) to maximum load was lower in alkaline solution by a maximum of 15.65% as compared to salt conditioning during 6 months of aging.

Overall, reductions in ratio of loads at limiting crack widths (0.016”) to respective maximum loads due to aging were a maximum of 15.65%. It should be noted that this reduction involves the effect of aging on all beam components including steel reinforcement, concrete and CFRP wrap.

9.5 CONCLUSIONS FOR DEFORMABILITY FACTOR

Water immersion aging

- The average deformability factors decreased with increase of temperature and aging duration:
  - *At 9 months*: from 11.93 at room temperature to 10.43 at 140°F temperature
  - *At 140°F temperature*: from 12.00 at 3 months to 10.43 at 9 months

Alkaline and salt immersion aging at room temperature

- The deformability factors of beams aged in alkaline solution are slightly lower than those for beams aged in salt solution for both types of bottom and U-shaped wrapping (13.14 in alkaline solution versus 13.29 in salt solution for bottom wrapped beam; and 15.93 in alkaline solution versus 16.67 in salt solution for U-shape wrapped beam). Increased deformability factors in U-shape wrapped beams are mainly due to increased moment capacities providing additional energy absorption capability.

Alkaline and salt immersion aging under freeze-thaw conditioning

- The deformability factors of beams aged in alkaline solution are lower than those for beams aged in salt solution for both types of bottom and U-shaped wrapping (12.29 in alkaline solution versus 14.09 in salt solution for bottom wrapped beam; and 14.74 in alkaline solution versus 15.62 in salt solution for U-shape wrapped beam). Increased deformability factors in U-shape wrapped beams are mainly due to increased moment capacities providing additional energy absorption capability.

Natural aging at constant 68 °F of room temperature

- Deformability factors for beams b2 and b3 having three layers and one layer of carbon fabric were found to be 11.64 and 14.76, respectively. It should be noted that the beam with three-layers of fabric results in decreased deflection and crack-width thus providing increased loads at which the limiting values of deflection, crack-width, and curvature are reached. Thus, increased energy absorption at limiting curvature, i.e., denominator term, gives an apparent lower deformability factor.

Natural aging at (outside weathering)

- Deformability factors of beams NA1 and NA3 were 10.33 and 11.63.
- Deformability factors were found to be higher than ten indicating good energy absorption in wrapped beams. U-shaped wraps provided better deformability factors, bending strengths and durability.

Overall, deformability factors were found to be higher than 10 indicating good energy absorption in wrapped beams. U-shaped wraps provided better deformability factors, bending strengths and durability

9.6 CONCLUSIONS FOR STRENGTH AND STIFFNESS OF CARBON FIBER STRIPS

Maximum strength and stiffness reductions in CFRP strips under different conditioning schemes were:

Aging schemes	**Strength reduction**	**Stiffness reduction**
Water immersion aging (140F, 9 months)	12.90%	5.92%
Alkaline and salt immersion aging at room temperature (3 months)	6.45%	5.61%
Alkaline and salt immersion aging under freeze-thaw conditions (6 months)	9.68%	7.48%
Natural aging (constant 68°F, 3 years)	10.6%	7.40%
Natural aging (outside weathering, 3.5 years)	6.45%	4.99%

9.7 CONCLUSIONS FOR EFFECT OF AGING ON TENSILE AND BOND STRENGTHS

- Using the experimental and theoretical studies from Vijay and GangaRao (1999) and Barger (2000), 23% of maximum reduction in bond strength values obtained in accelerated aging study is conservatively extrapolated to be equivalent to the loss in about 30 years of service life.
- Average bond strength reductions were found to be less than 10% in the study by Barger (2000), which would indicate better bond performance during service life of wrapped structures.

9.8 CONCLUSIONS FOR COMPARISON OF WRAPPED AND NON-WRAPPED CONCRETE BEAMS

- Maximum increase in beam bending moment due to one layer of CFRP wrap was found to be 113.5%. Similarly, loads to limiting deflection values and crack-widths showed significant increase of 75% or more in wrapped as compared to beams without wrapping. Magnitude of moment capacity increase, and reductions in deflection and crack width due to wrapping depend upon beam dimensions, internal reinforcement properties (e.g., area and yield strength), and number of carbon wrap layers.

9.9 CONCLUSIONS FOR CORRELATION OF ACCELERATED AND NATURAL AGING

- In this research, maximum strength reduction in CFRP strips aged naturally under atmospheric (outside) weathering was 6.5 %. However, research results of others indicated a CFRP/epoxy strength reduction of 3.5% over 3 years near Miyakojima Island of Okinawa, Japan, which may be attributed to lower thermal fluctuation in Okinawa than in Morgantown, WV. Strength reductions are typically higher during initial aging duration and then tend to reduce dramatically with time.
- Based on the correlation of accelerated aging to natural aging, 12.9 % strength reduction in carbon wraps bonded to concrete beams aged under 140°F for 9 months in our study is equivalent to 82 years.
- Reduction factor of 0.85 imposed by ACI 440 for CFRP fabrics subjected to normal and aggressive outside exposure is conservatively justified because the test results indicate 12.9% reduction in 82 years.
- Maximum strength reduction of 12.9% was observed in CFRP strips aged in water at 140F temperature as compared to other aging schemes. Maximum stiffness reductions were 7.48% for specimens aged in alkaline and salt solution under freeze-thaw conditioning. These values were utilized for correlating accelerated aging to natural weathering.

9.10 RECOMMENDATION FOR DESIGNERS

From the perspective of a structural designer, following conclusions and suggestions are made:

- Wrapping concrete beams with FRP fabrics improves the flexural strength and stiffness of the beam. Other methods such as shear enhancement are not within the scope of this study and not discussed.
- Flexural strength and stiffness increase due to wrapping depend upon properties of the beam such as dimensions, f_c', existing properties and area of internal steel reinforcement and properties and area of external FRP reinforcement.
- U-shaped wraps provide better energy absorption and durability as compared to one-sided bottom wrapping.
- Deflections and crack-width are reduced due to wrapping.
- Reduction factor of 0.85 imposed by ACI 440 for CFRP fabrics subjected to normal and aggressive outside exposure is conservatively justified because the test results indicate 12.9% reduction in 82 years.

9.11 RECOMMENDATION FOR FUTURE RESEARCH

To predict the in-service life of a wrapped concrete member, following research is necessary:

- Assessing the activation energy contribution towards strength and stiffness degradation of the wrapped beams under different aging schemes.
- Comparing the degradation rate and activation energy in aged FRP strips extracted from both edge and interior locations of a wrap, both with and without sustained stresses, including Scanning Electron Microscopy (SEM) evaluation.
- Assessing the effectiveness of additional transverse wraps (U-wraps) in reducing the moisture ingress, protecting the interfacial bond line and reduction in steel reinforcement corrosion through physical removal and evaluation of bars.

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Appendix A

LOAD-DEFLECTION DIAGRAMS OF BEAMS AGED IN WATER

A.1: Load-deflection diagram of beams aged in water at room temperature

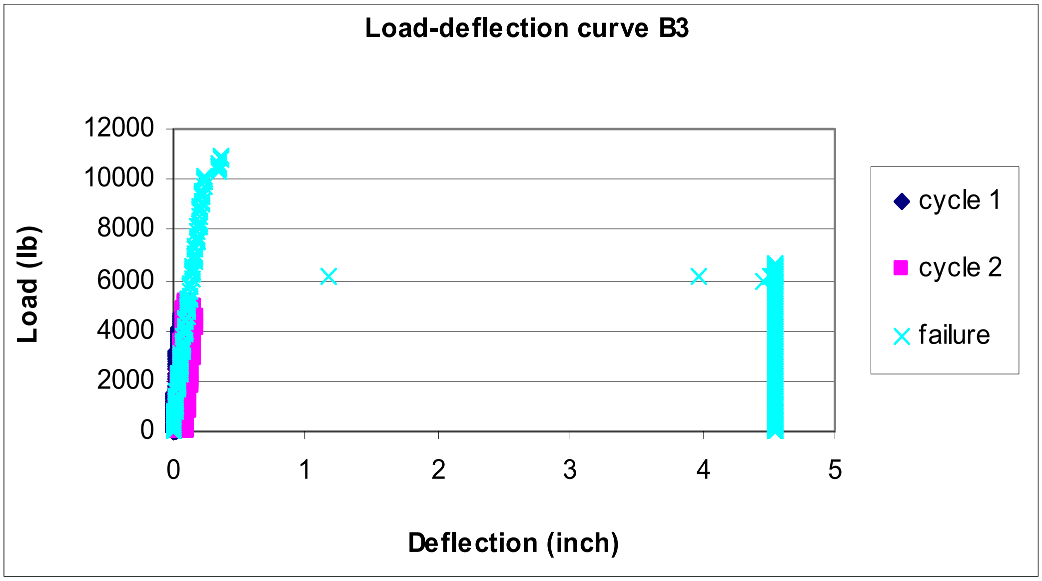

Fig A.1.1 Load-deflection curve of beam B3

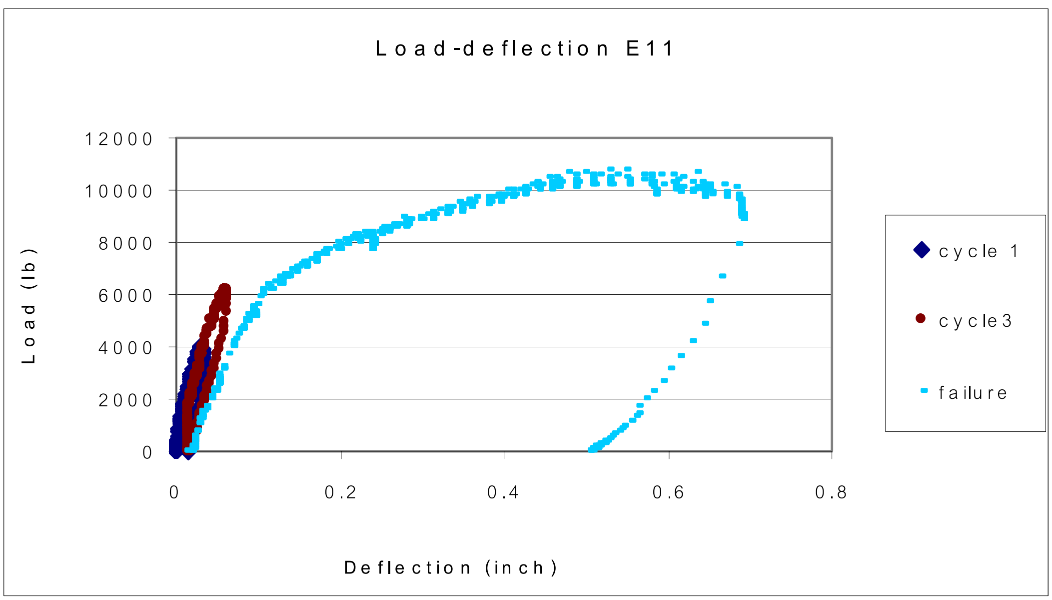

Fig A.1.2 Load-deflection curve of beam E11

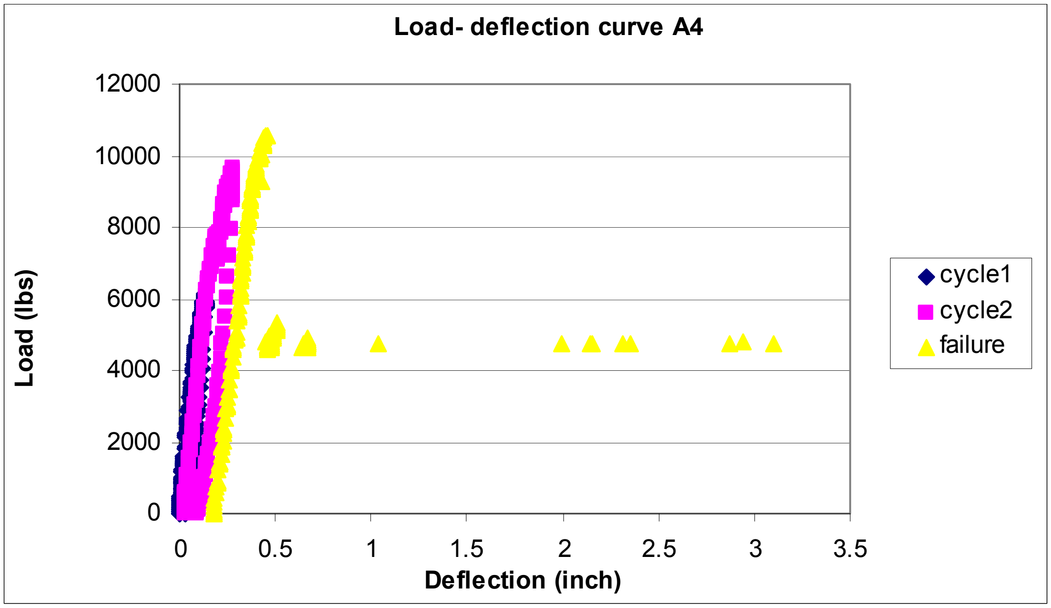

Fig A.1.3 Load-deflection curve of beam A4

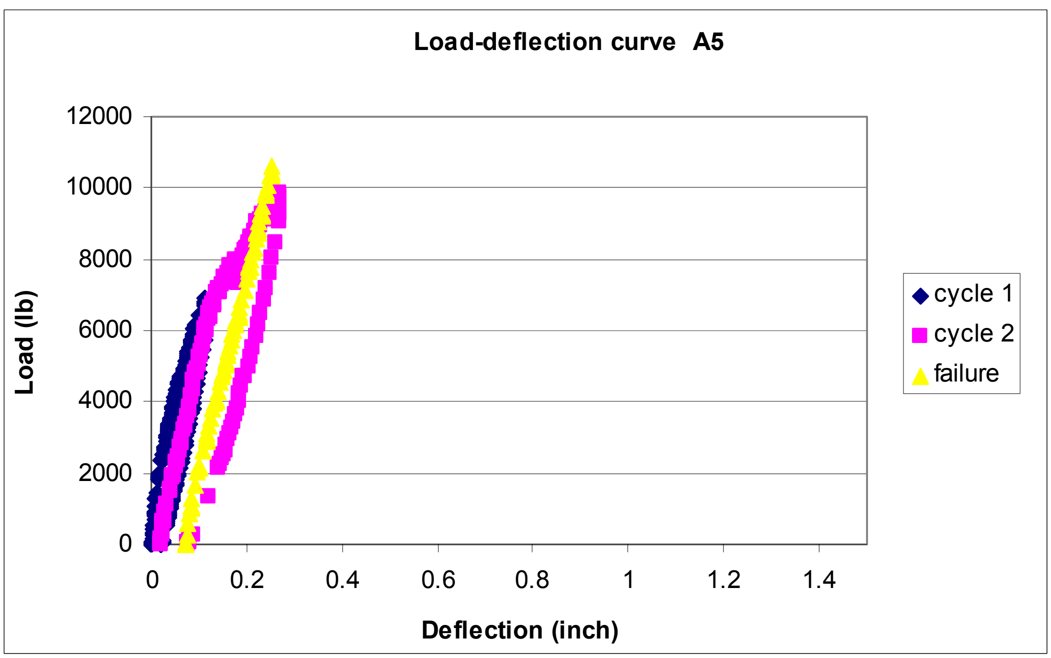

Fig A.1.4 Load-deflection curve of beam A5

A.2: Load-deflection diagram of beams aged in water at 110° F temperature

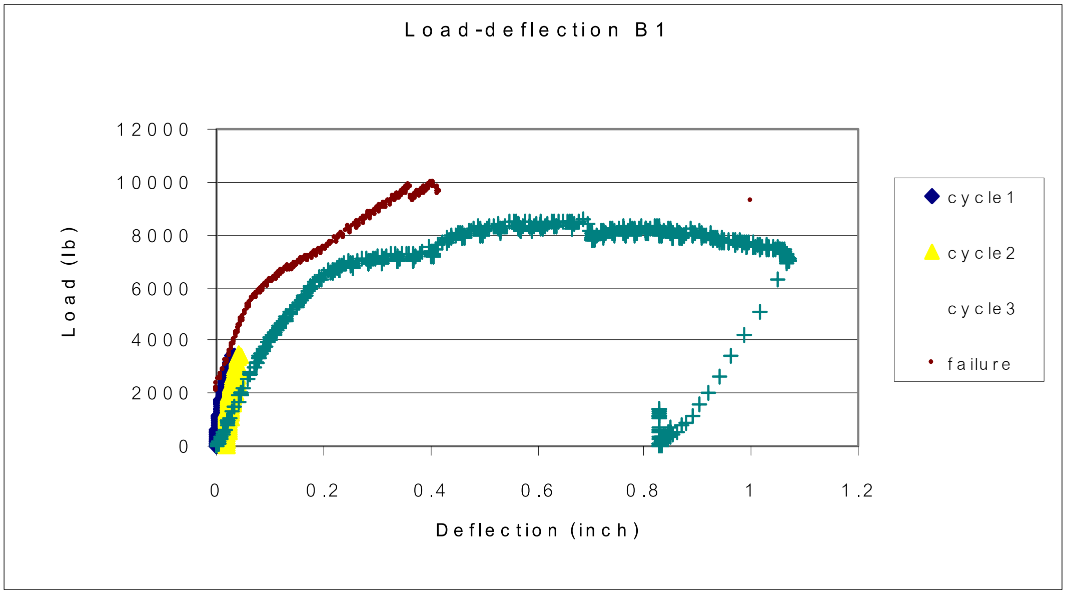

Fig A.2.1 Load-deflection curve of beam B1

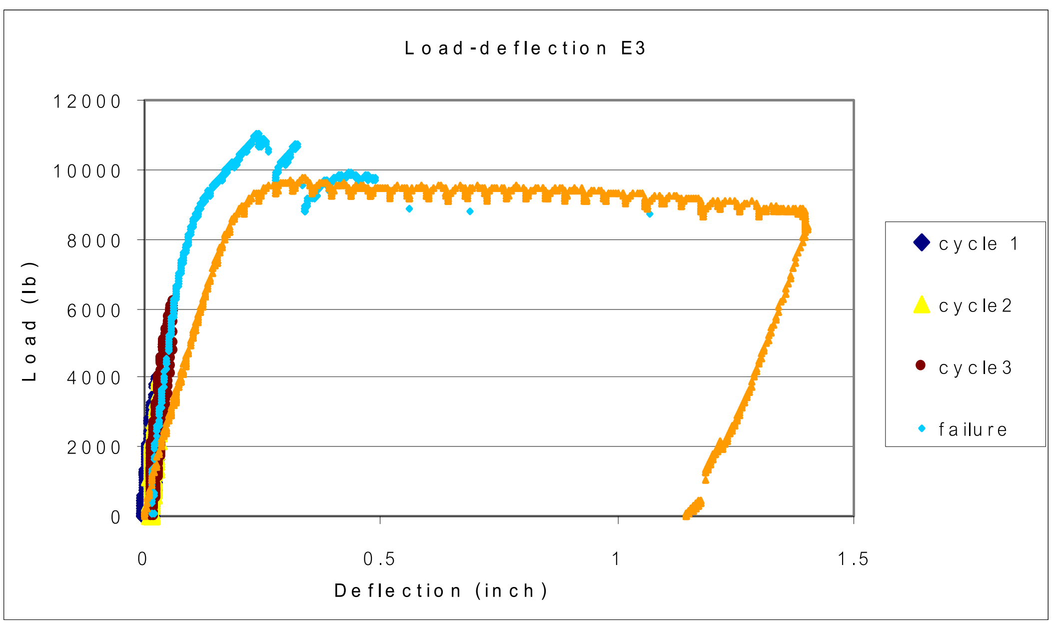

Fig A.2.2 Load-deflection curve of beam E3

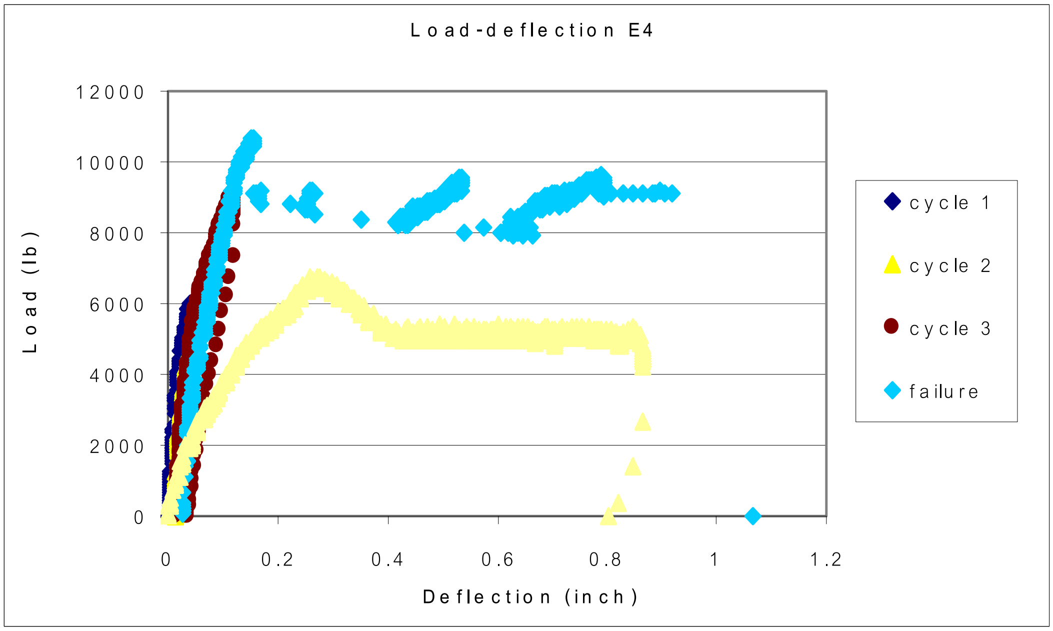

Fig A.2.3 Load-deflection curve of beam E4

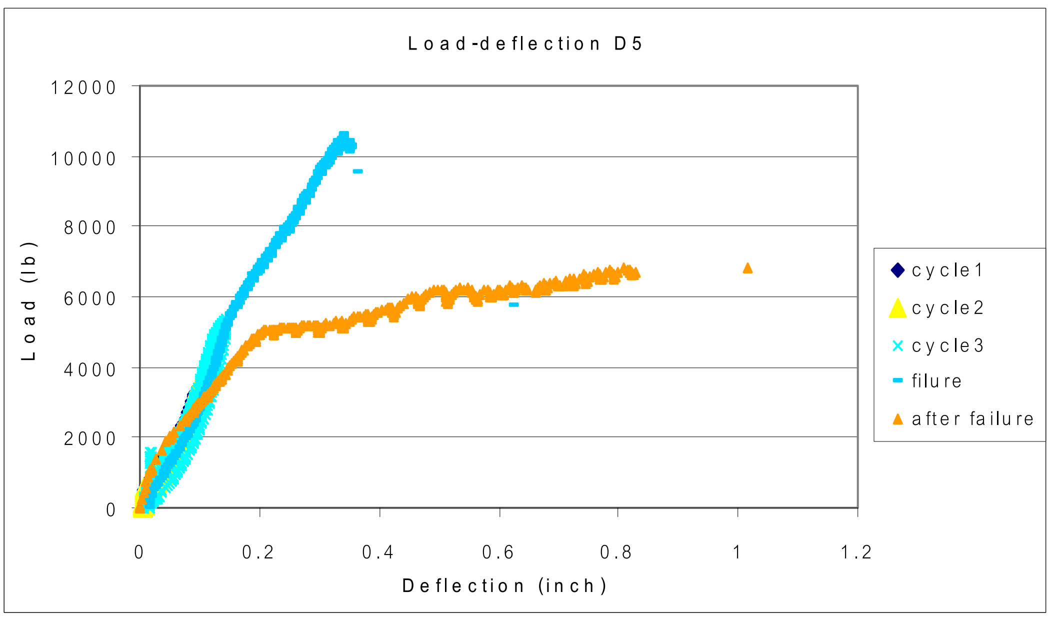

Fig A.2.4 Load-deflection curve of beam D5

A.3: Load-deflection diagram of beams aged in water at 140° F temperature

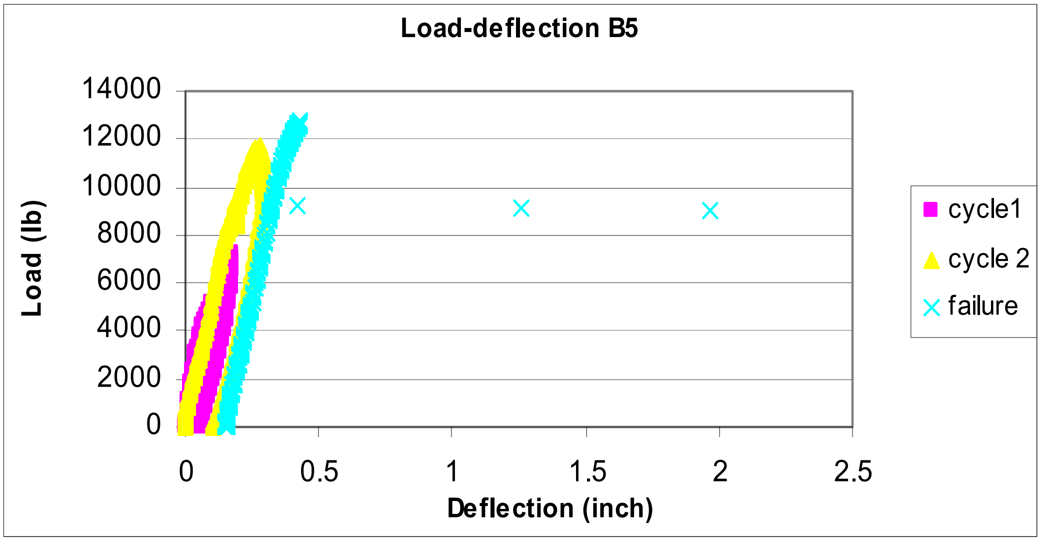

Fig A.3.1 Load-deflection curve of beam B5

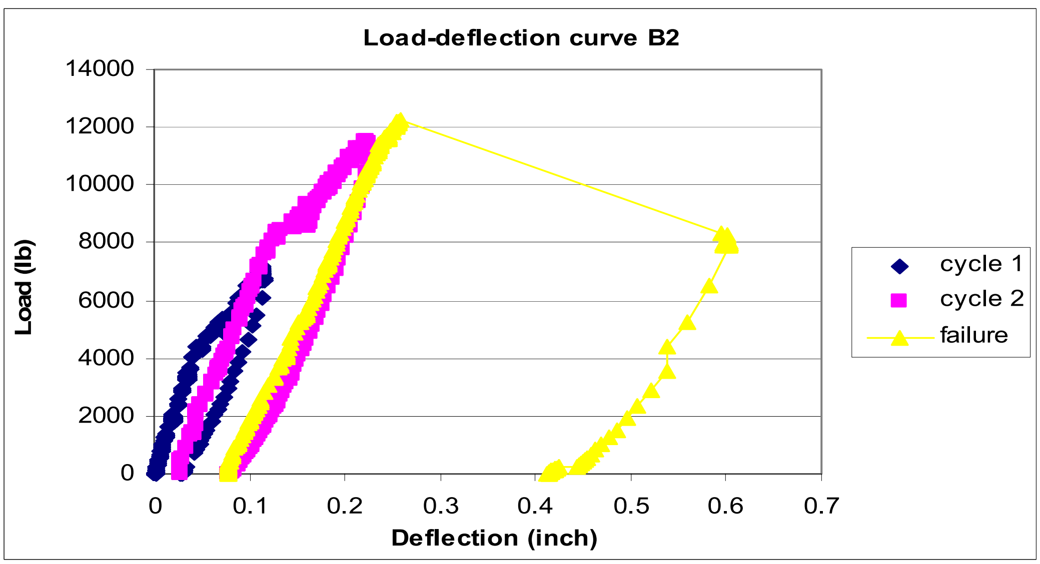

Fig A.3.2 Load-deflection curve of beam B2

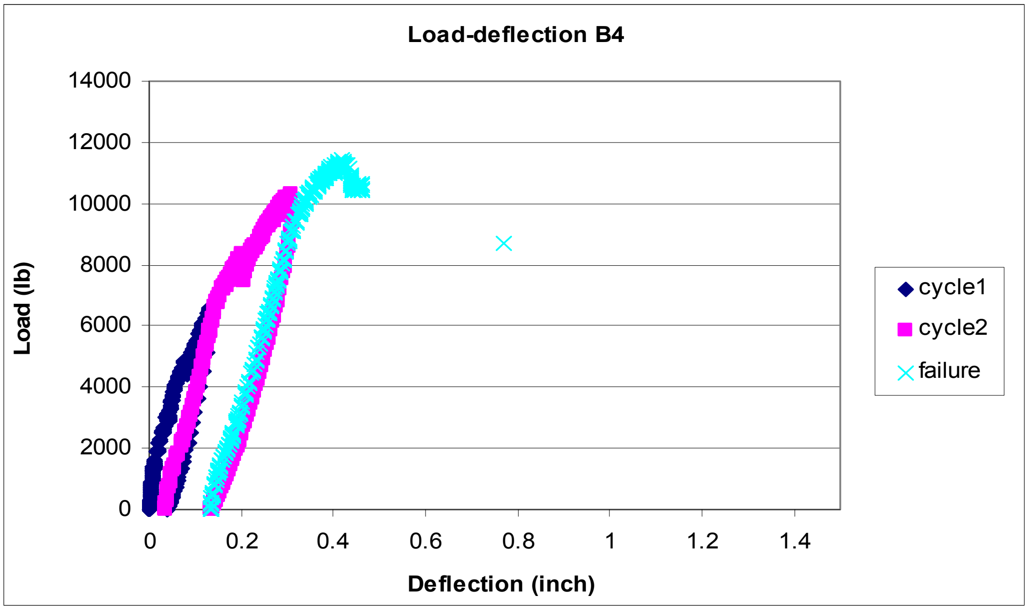

Fig A.3.3 Load-deflection curve of beam B4

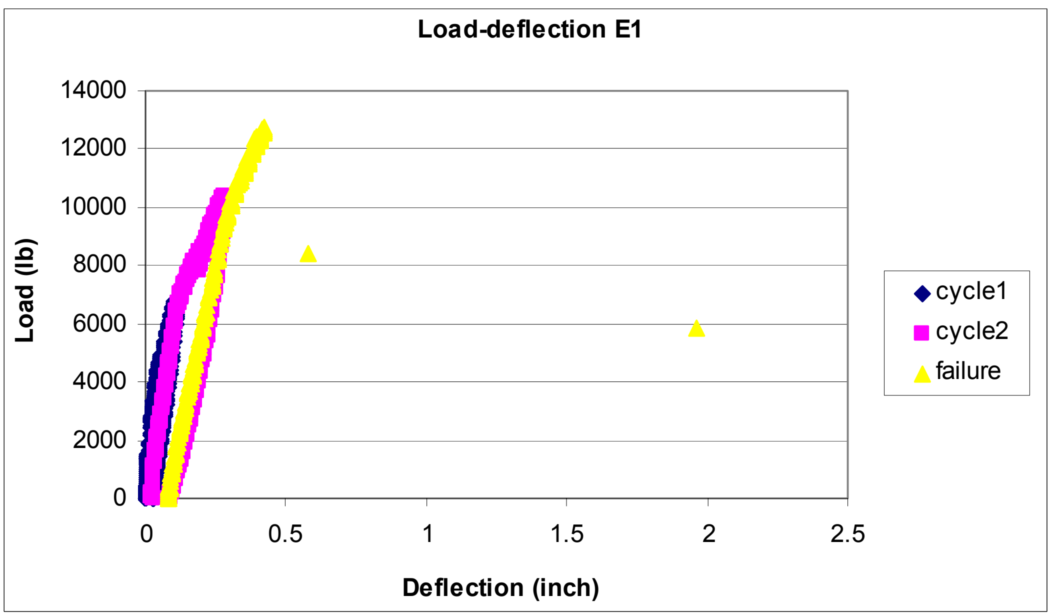

Fig A.3.4 Load-deflection curve of beam E1

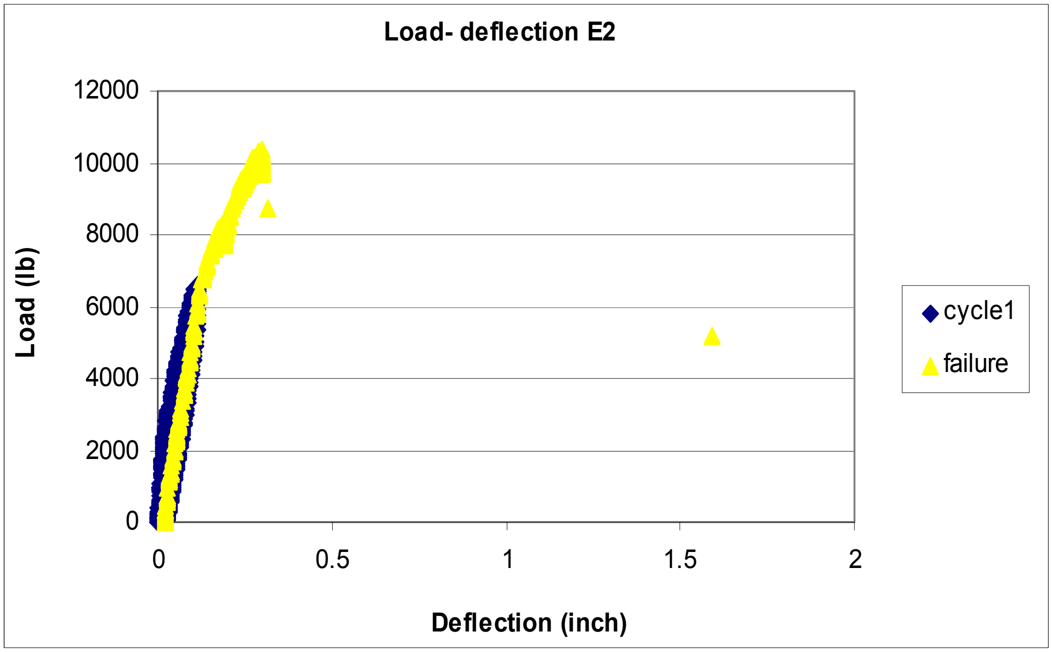

Fig A.3.5 Load-deflection curve of beam E2

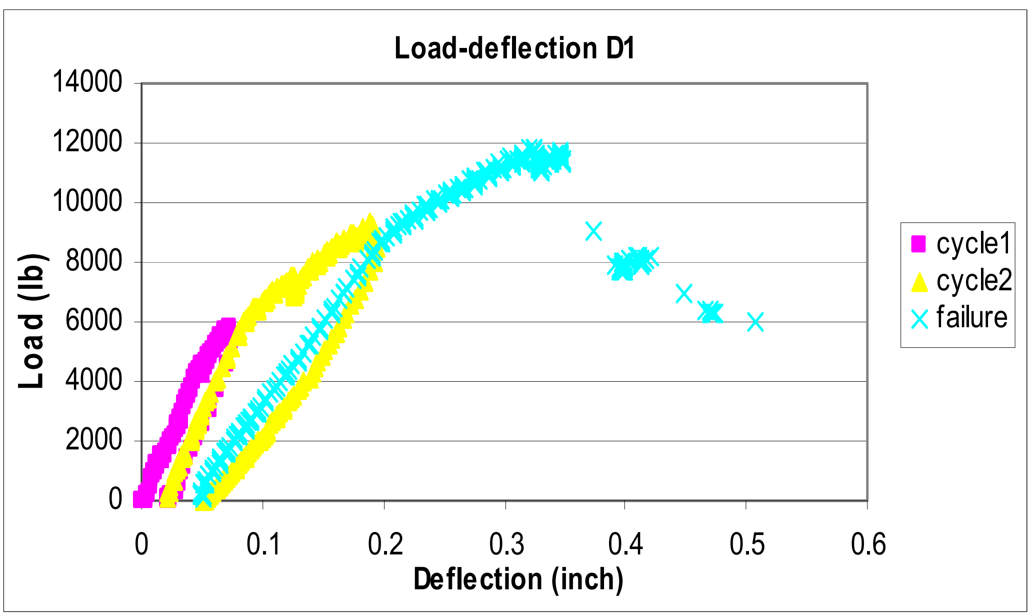

Fig A3.6 Load-deflection curve of beam D1

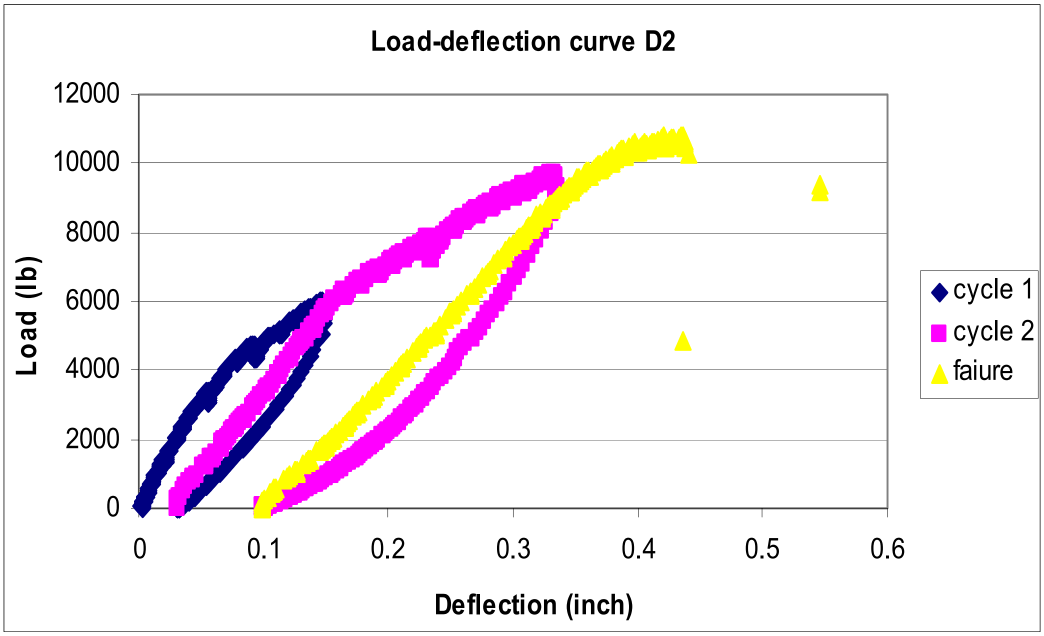

Fig A.3.7 Load-deflection curve of beam D2

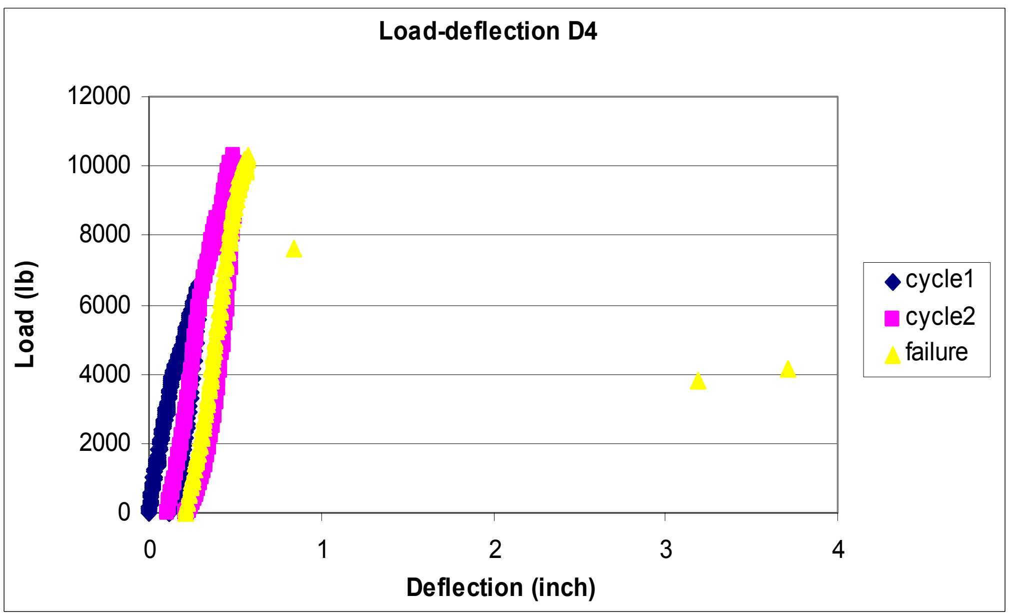

Fig A3.8 Load-deflection curve of beam D4

Appendix B

LOAD-DEFLECTON DIAGRAMS OF BEAMS AGED IN ALKALINE AND SALT SOLUTIONS

B.1: Load-deflection diagram of beams aged in alkaline and salt solutions at room temperature

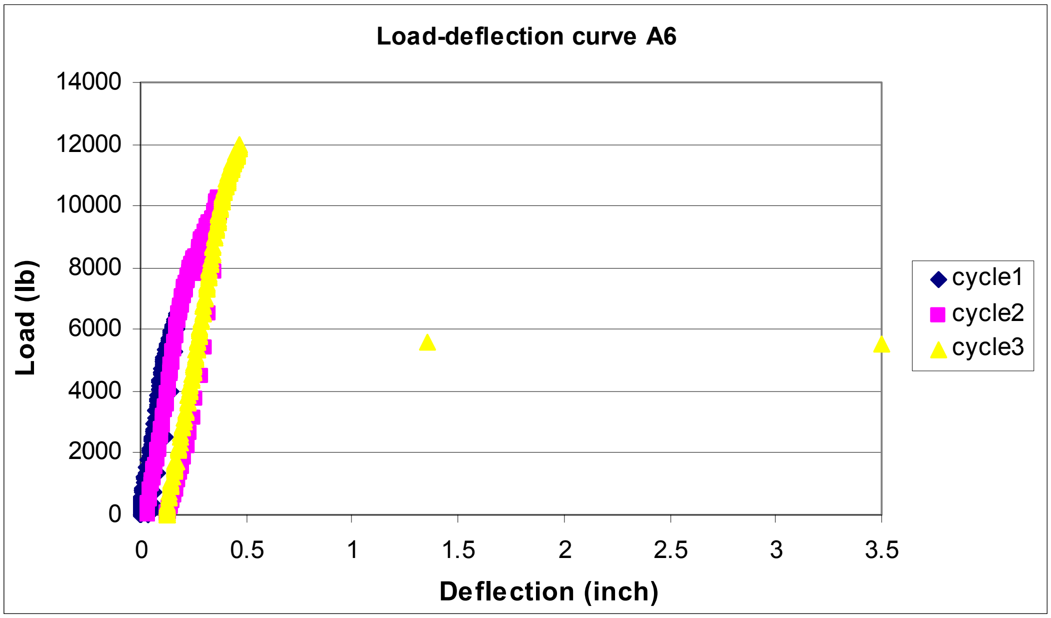

Fig B.1.1 Load-deflection curve of beam A6

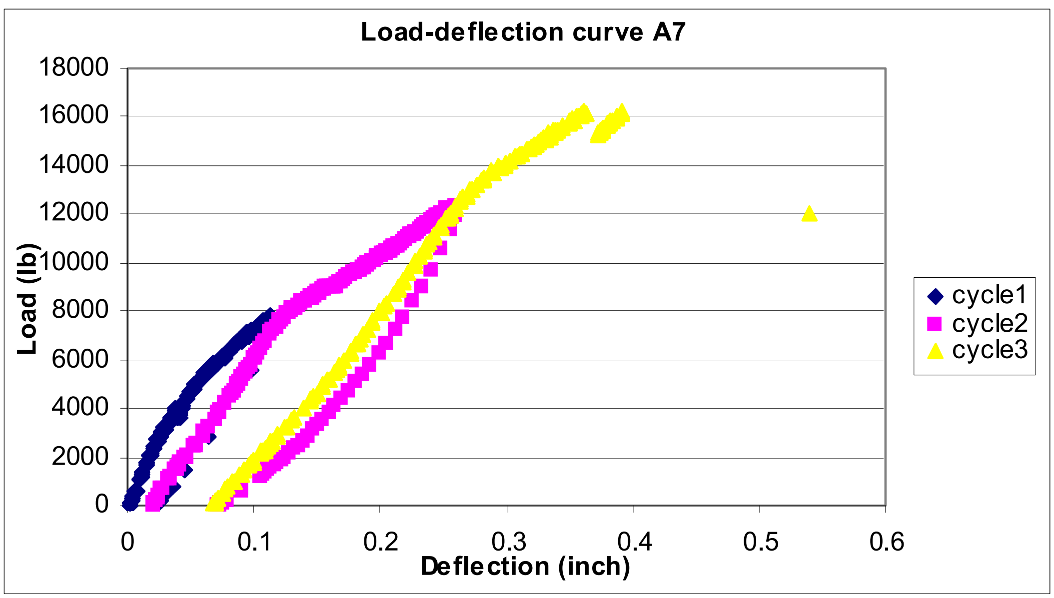

Fig B.1.2 Load-deflection curve of beam A7

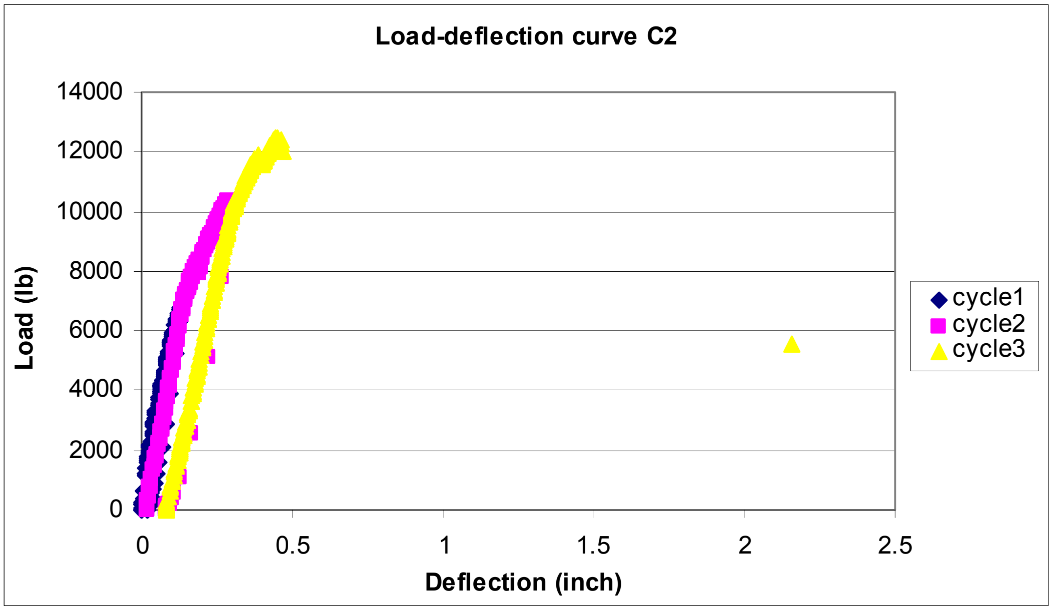

Fig B.1.3 Load-deflection curve of beam C2

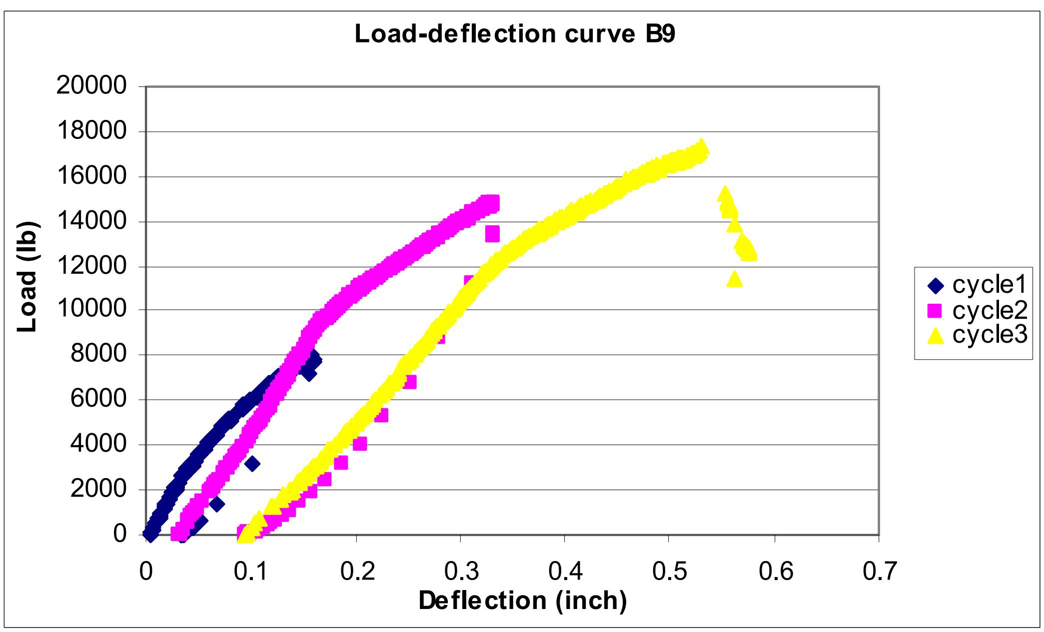

Fig B.1.4 Load-deflection curve of beam B9

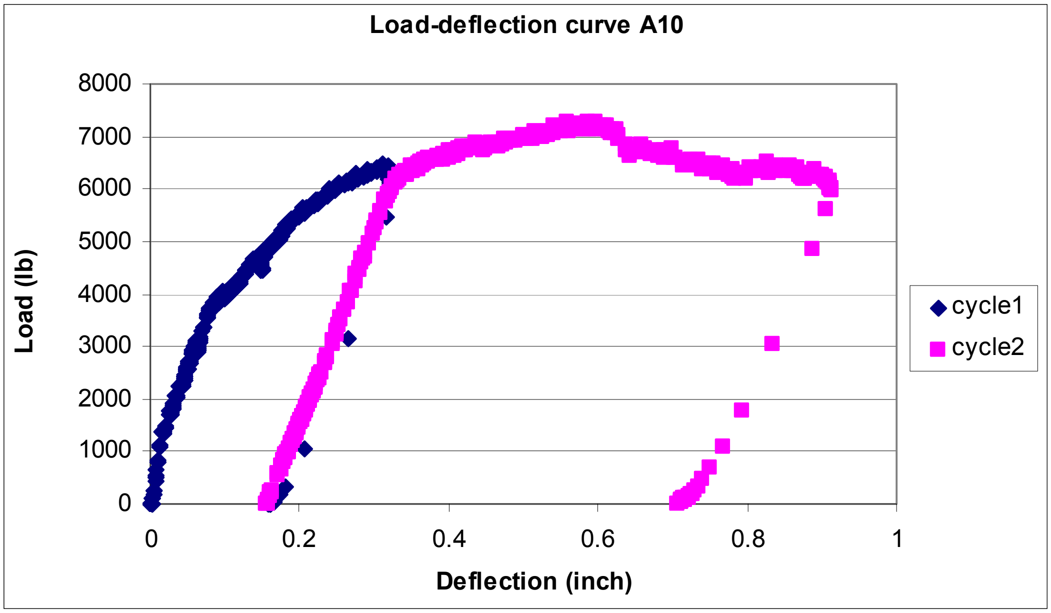

Fig B.1.5 Load-deflection curve of beam A10

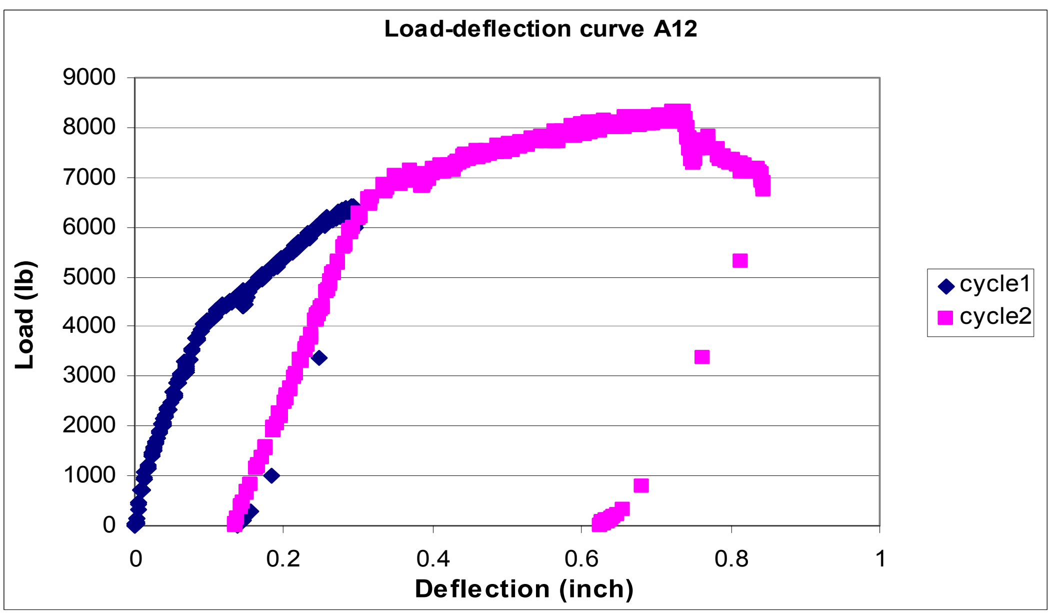

Fig B.1.6 Load-deflection curve of beam A12

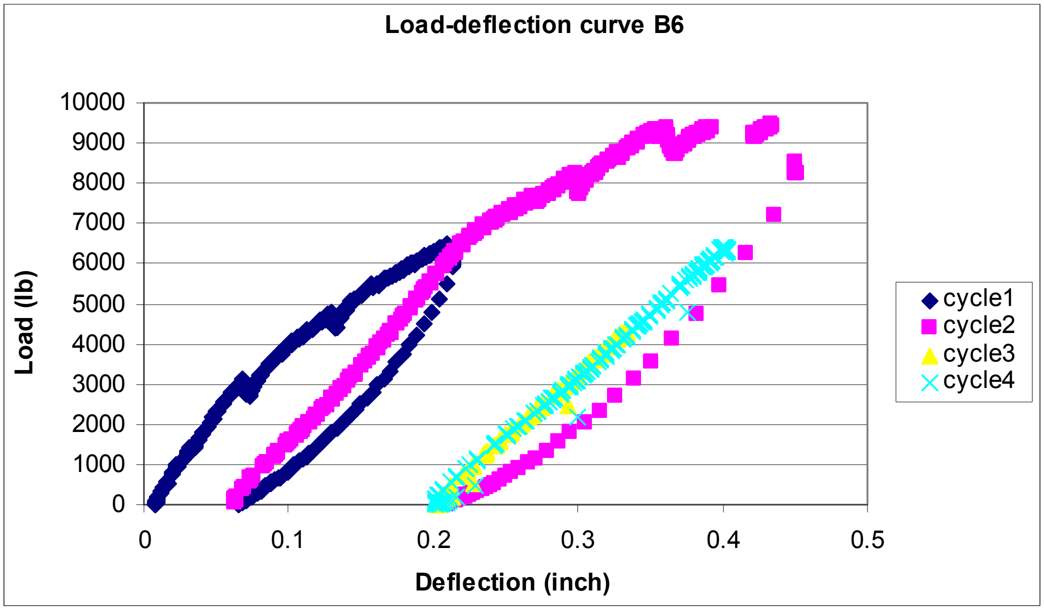

Fig B.1.7 Load-deflection curve of beam B6

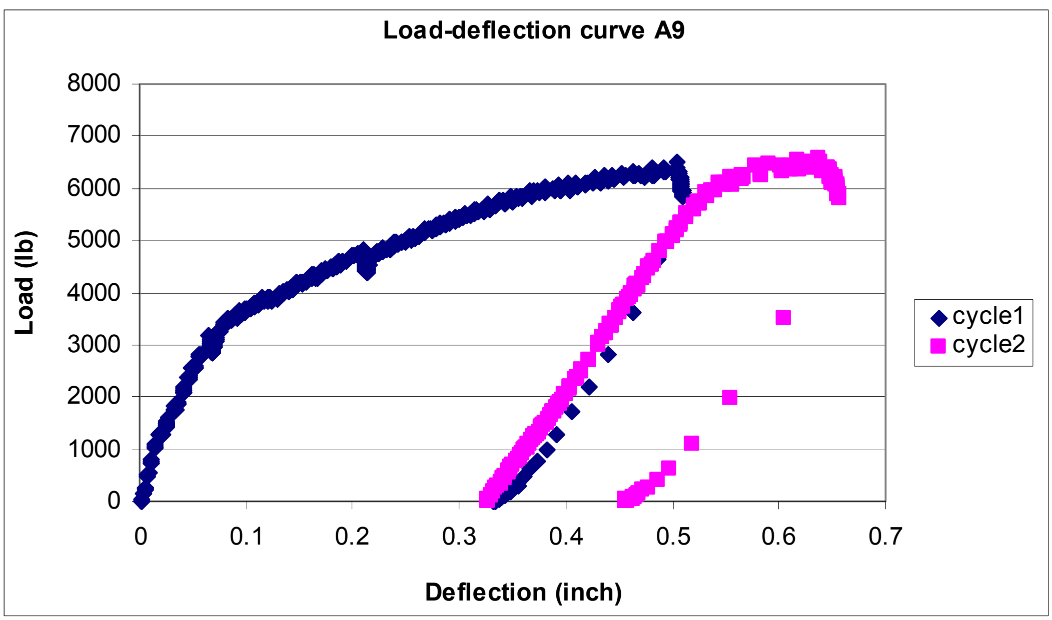

Fig B.1.8 Load-deflection curve of beam A9

B.2: Load-deflection diagram of beams aged in alkaline and salt solutions under freeze-thaw conditioning

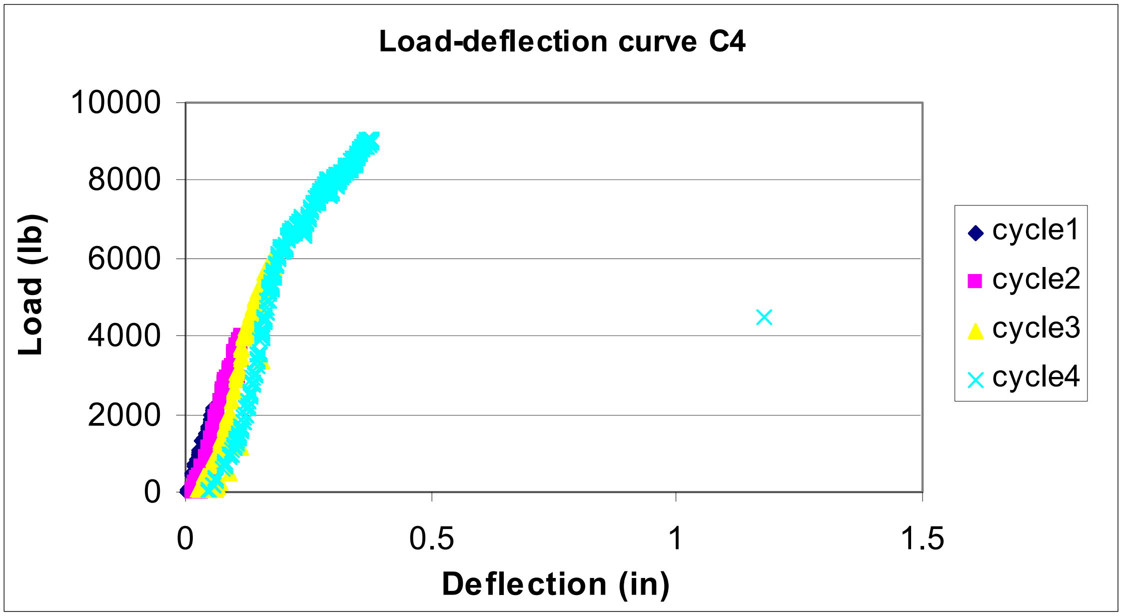

Fig B.2.1 Load-deflection curve of beam C4

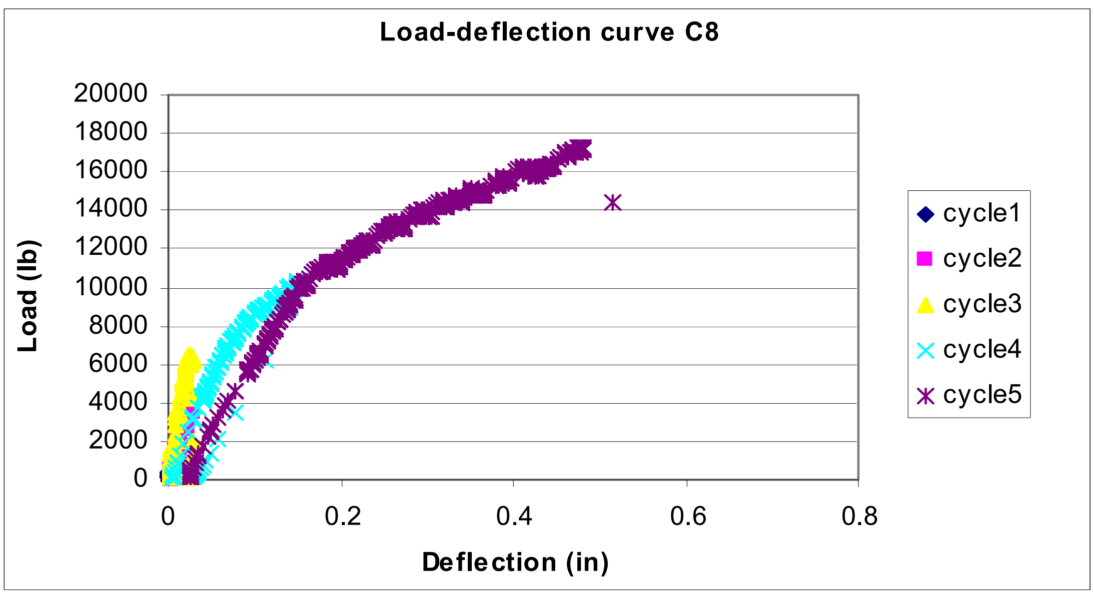

Fig B.2.2Load-deflection curve of beam C8

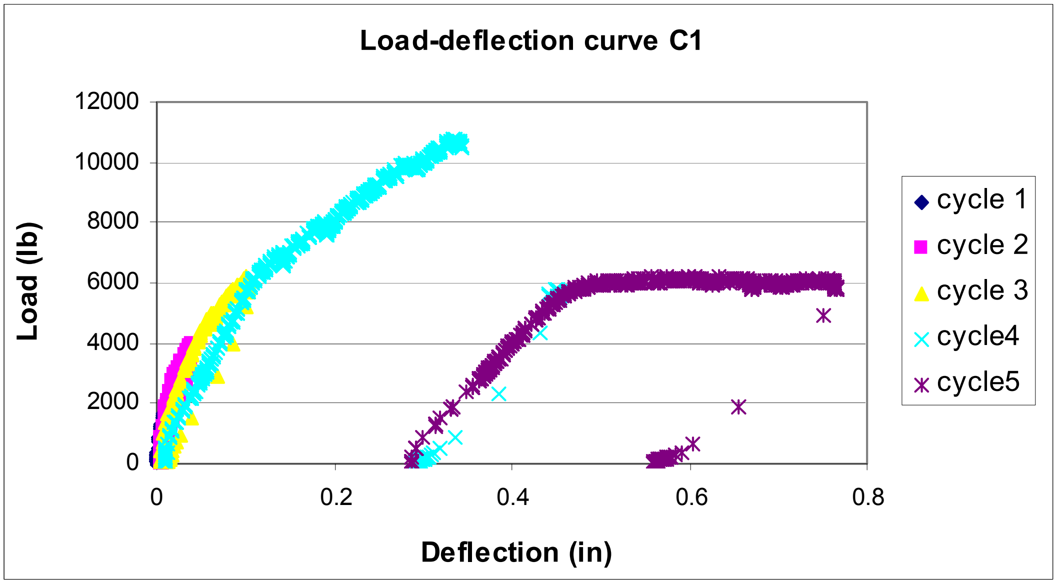

Fig B.2.3 Load-deflection curve of beam C1

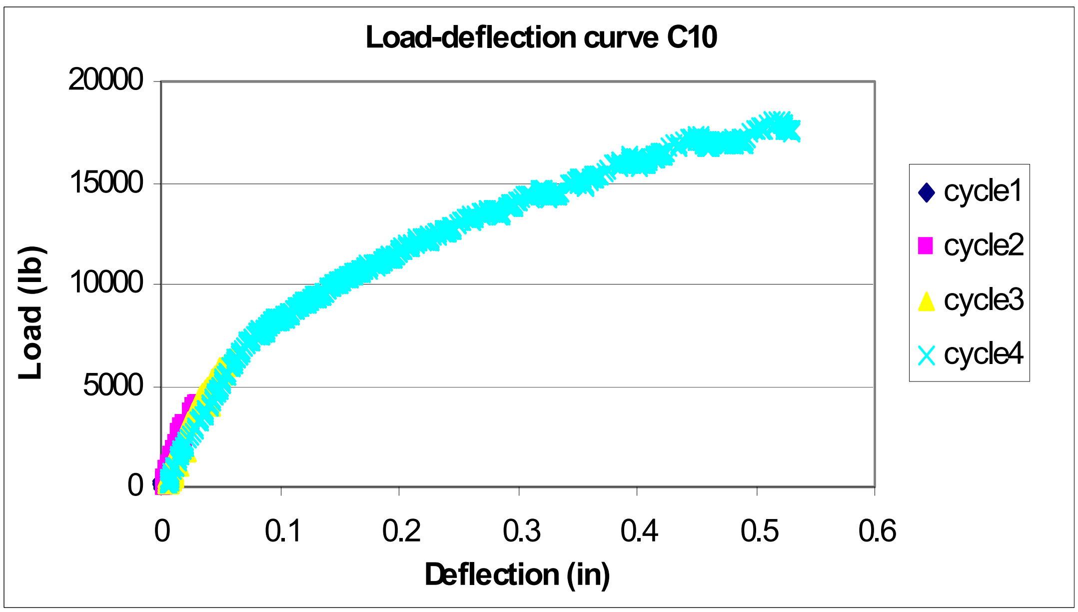

Fig B.2.4 Load-deflection curve of beam C10

Appendix C

LOAD-DEFLECTION DIAGRAMS OF BEAMS AGED UNDER OUTSIDE WEATHERING

C.1: Load-deflection diagram of beams aged naturally outside

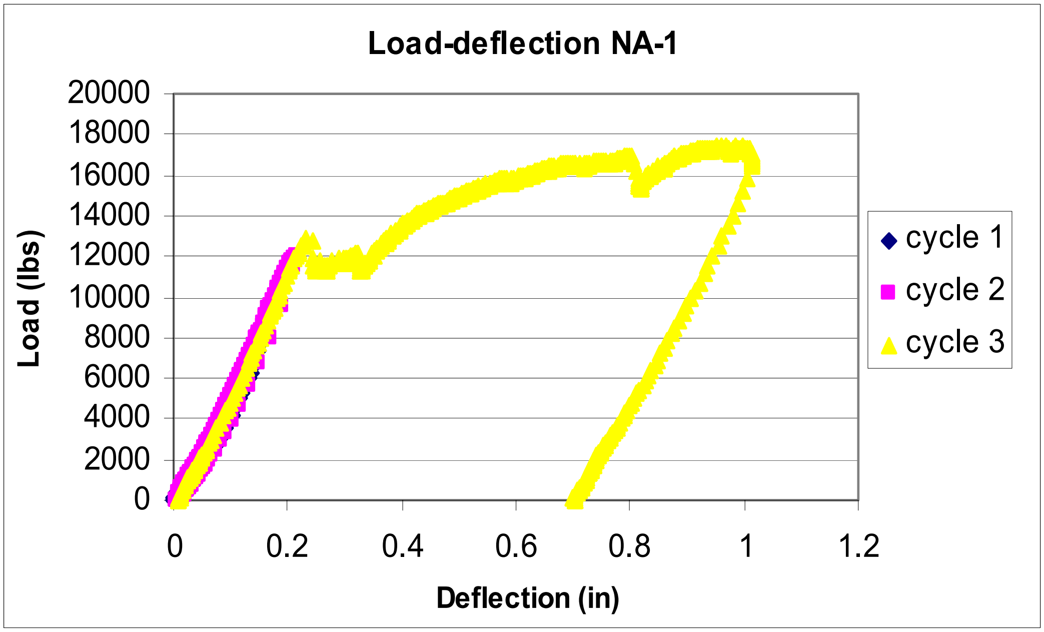

Fig C.1.1 Load-deflection curve of beam NA1

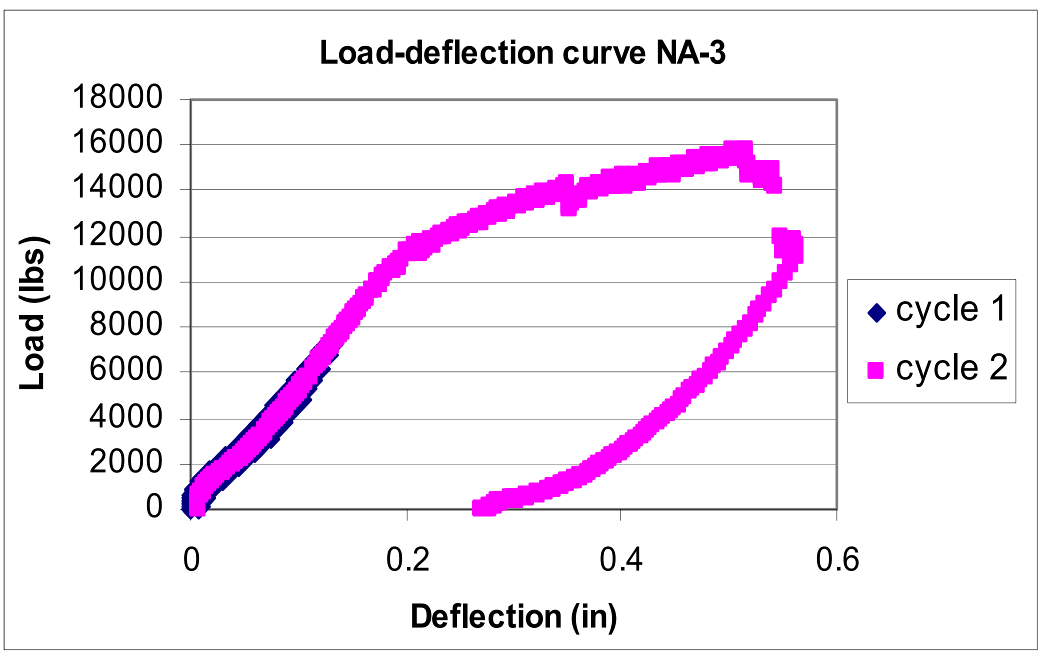

Fig C.1.2 Load-deflection curve of beam NA3

Appendix D

LOAD-CRACK WIDTH DIAGRAMS OF BEAMS AGED IN WATER

D.1: Load-crack width diagram of beams aged in water at room temperature

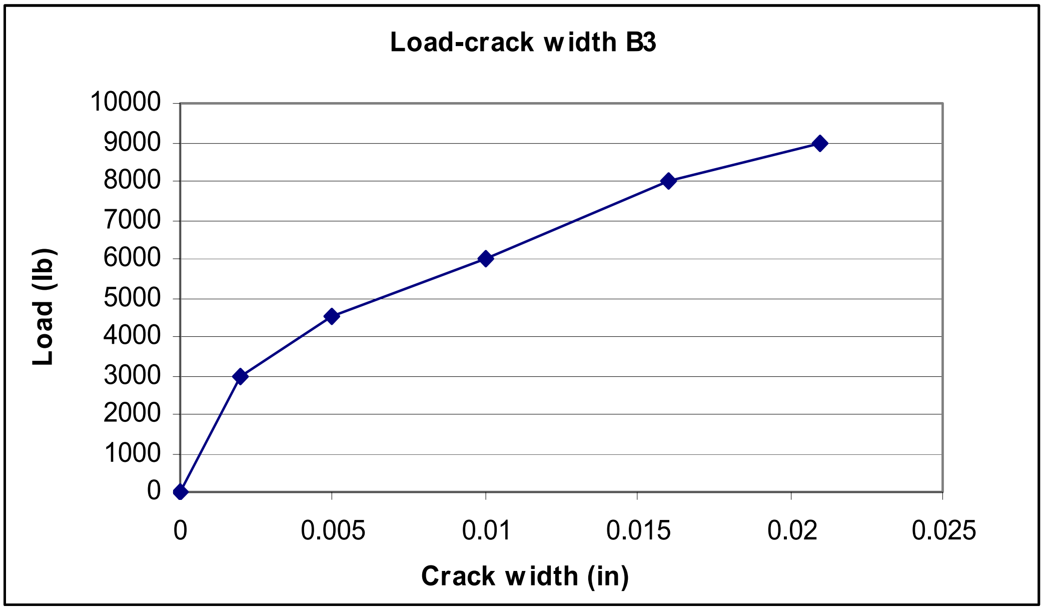

Fig D.1.1 Load-crack width curve of beam B3

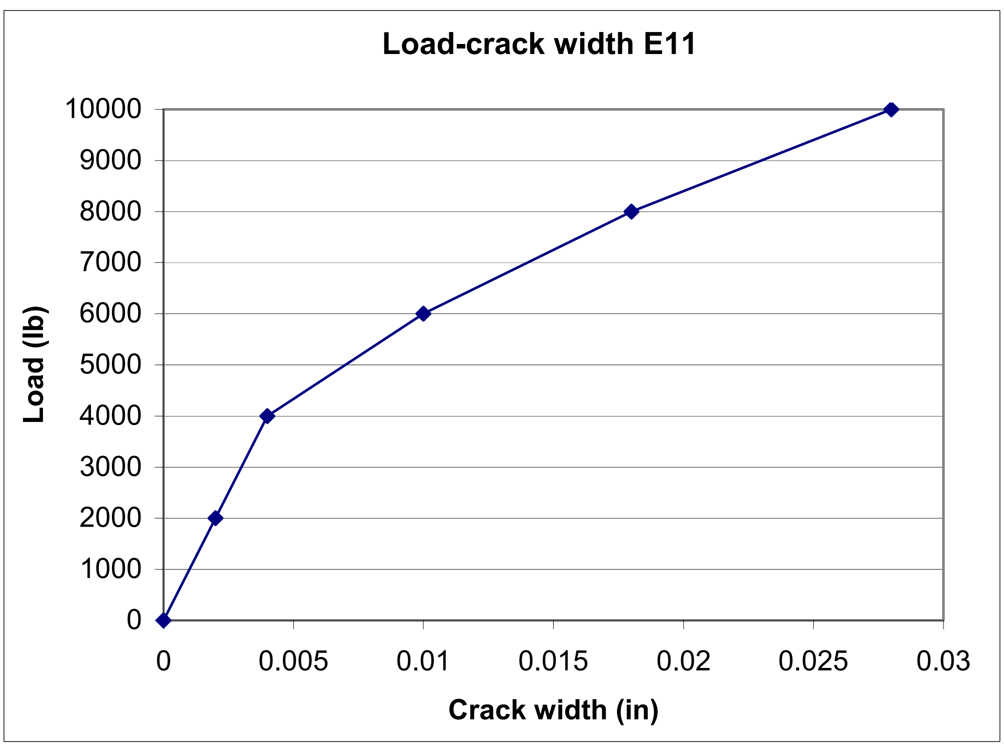

Fig D.1.2 Load-crack width curve of beam E11

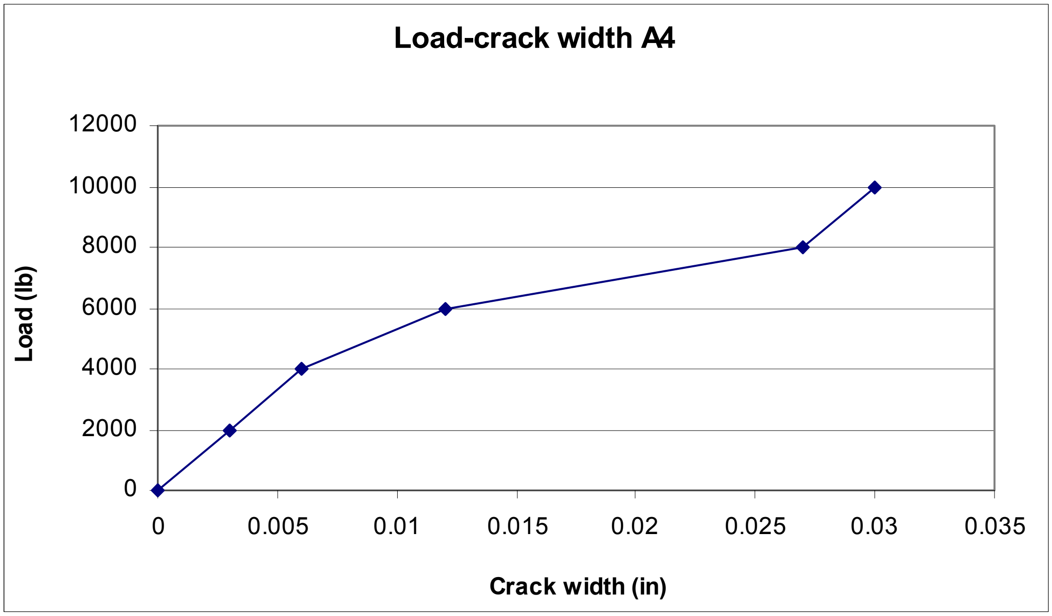

Fig D.1.3 Load-crack width curve of beam A4

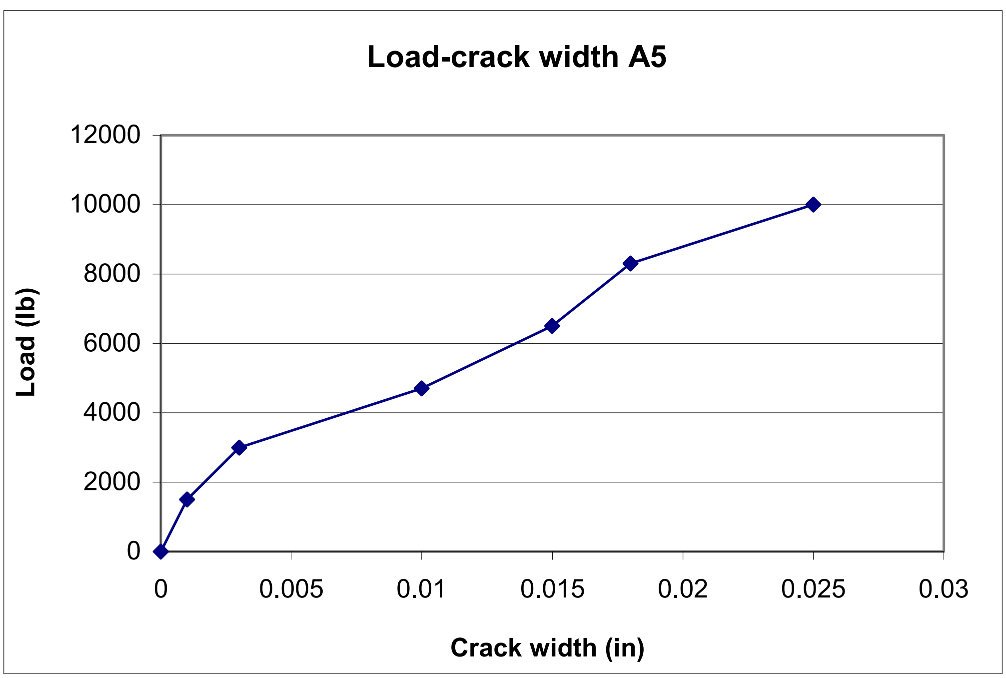

Fig D.1.4 Load-crack width curve of beam A5

D.2: Load-crack width diagram of beams aged in water at 110 °F temperature

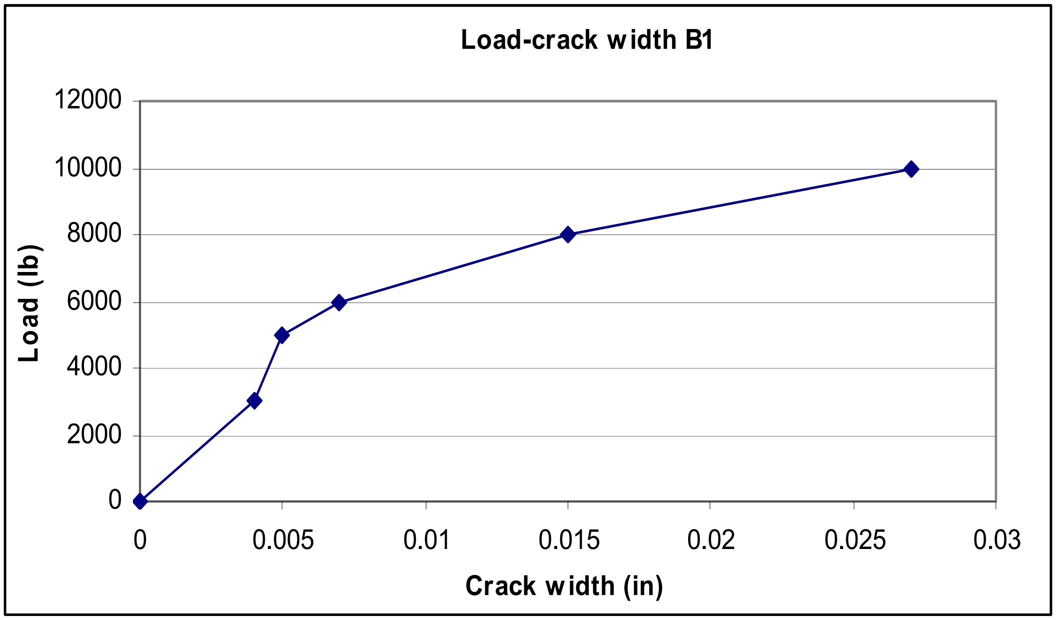

Fig D.2.1 Load-crack width curve of beam B1

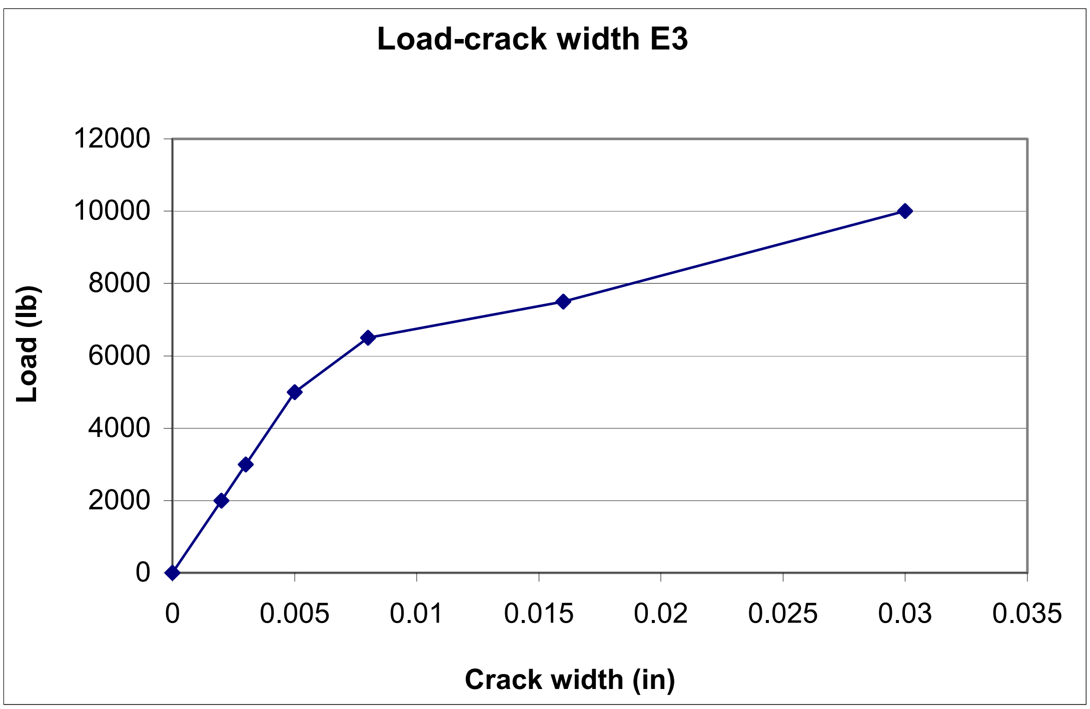

Fig D.2.2 Load-crack width curve of beam E3

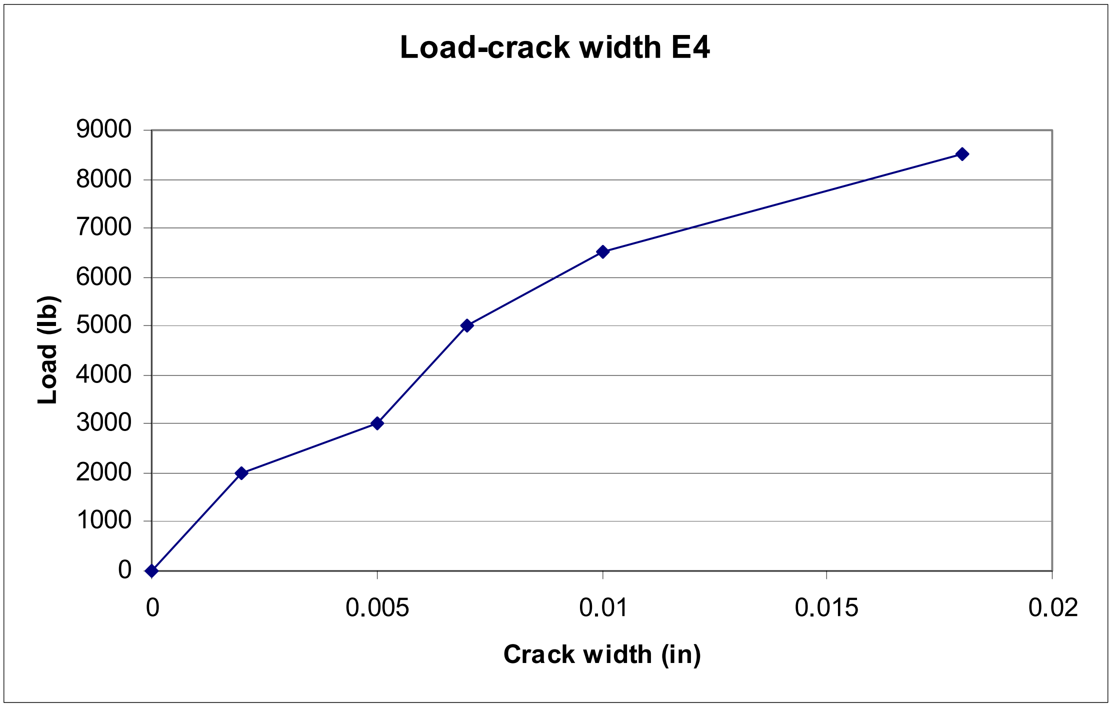

Fig D.2.3 Load-crack width curve of beam E4

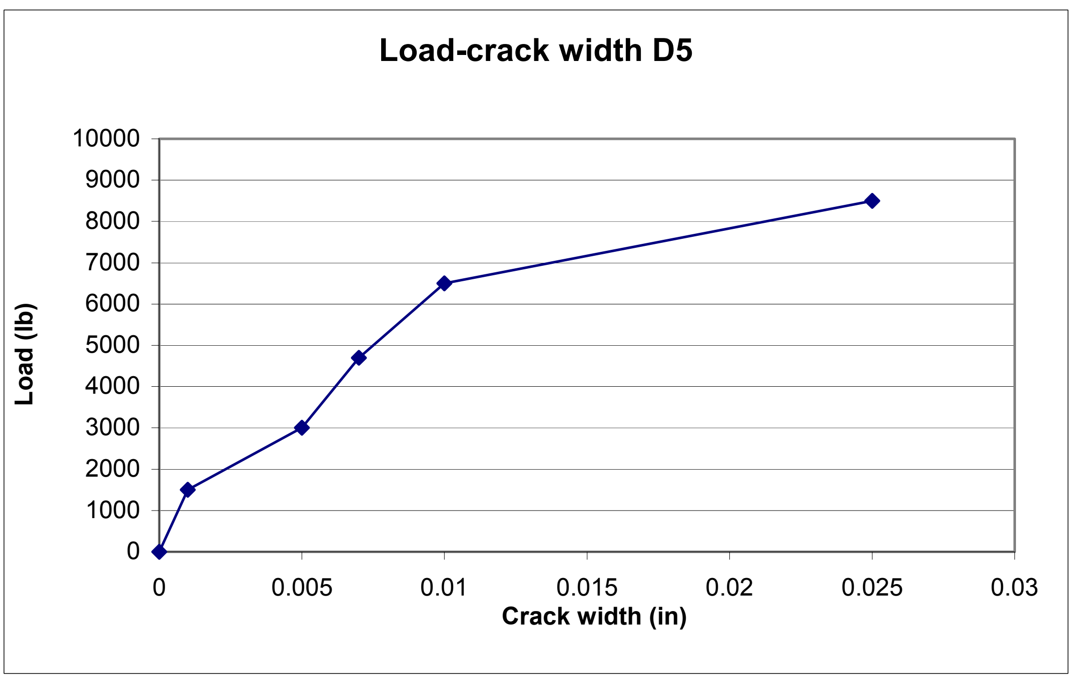

Fig D.2.4 Load-crack width curve of beam D5

D.3: Load-crack width diagram of beams aged in water at 140 °F temperature

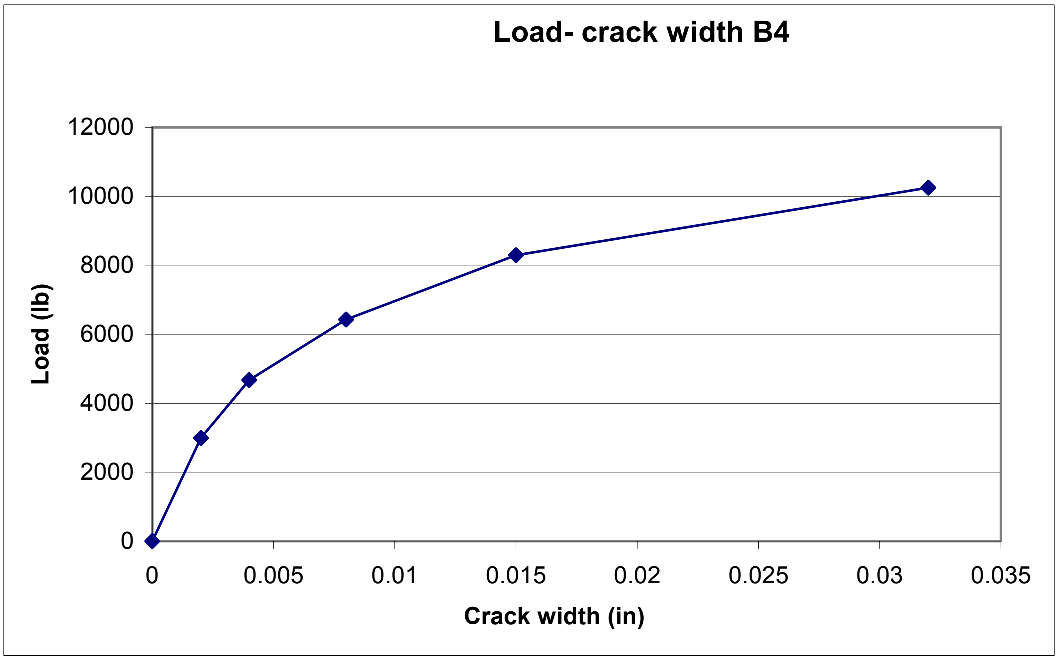

Fig D.3.1 Load-crack width curve of beam B4

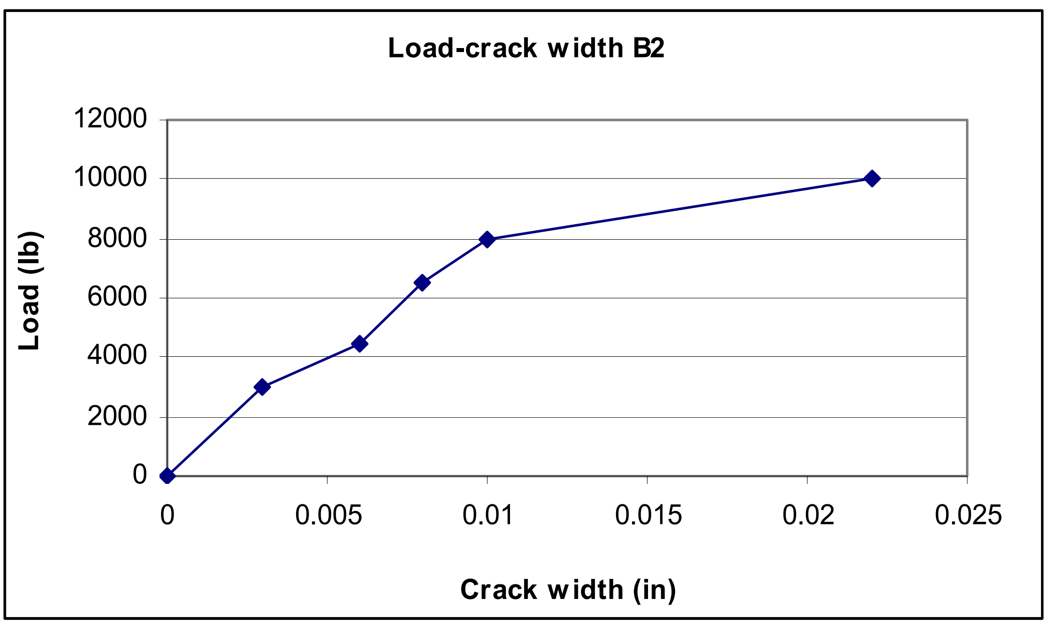

Fig D.3.2 Load-crack width curve of beam B2

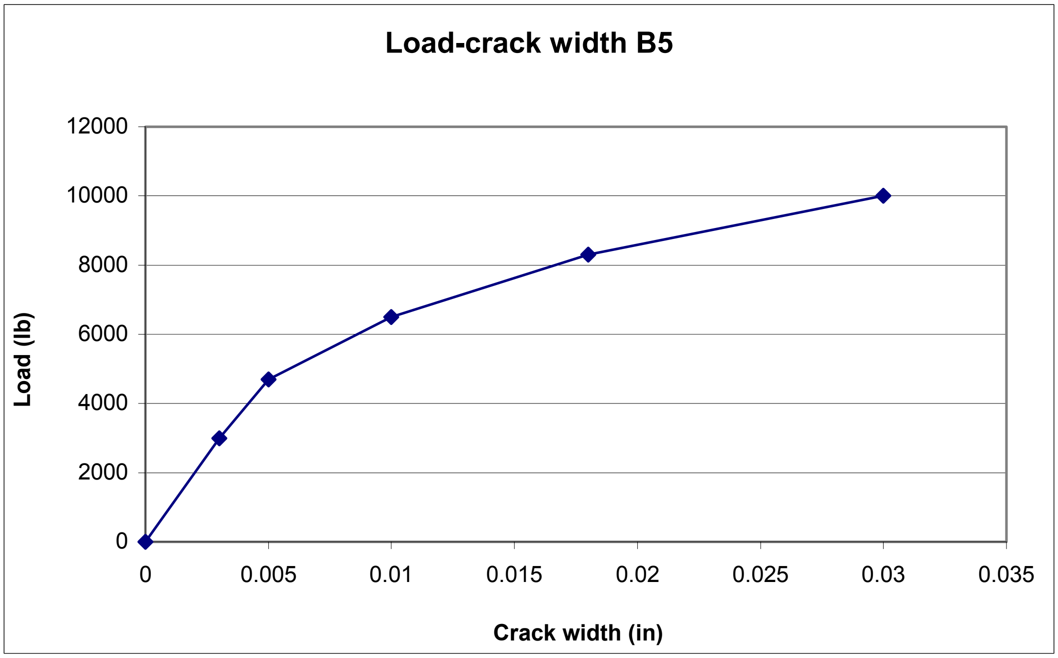

Fig D.3.3 Load-crack width curve of beam B5

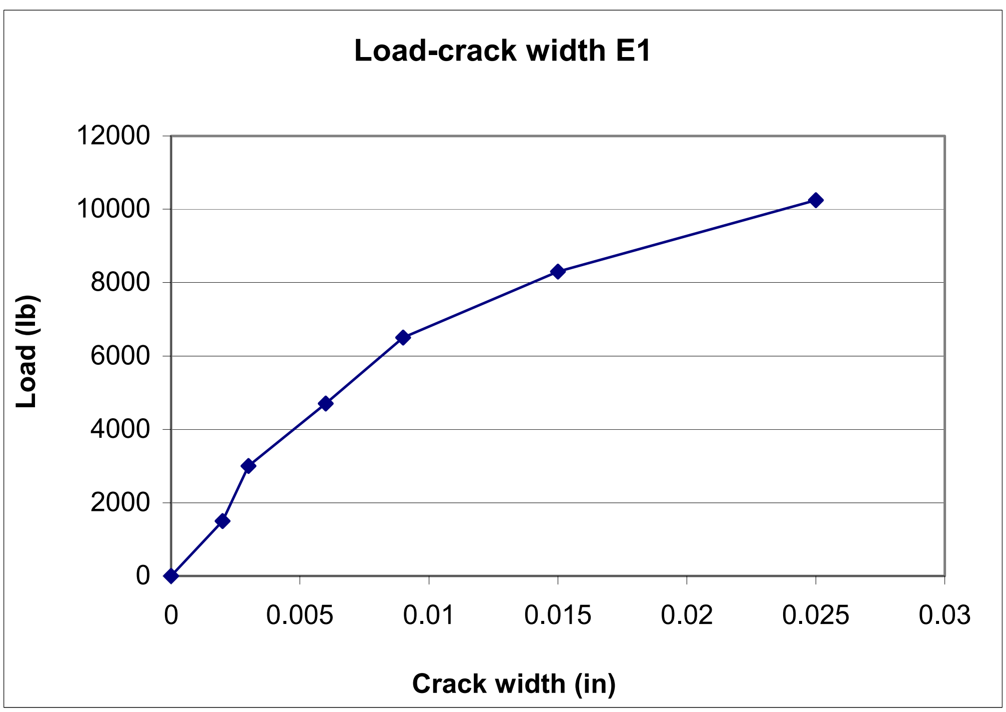

Fig D.3.4 Load-crack width curve of beam E1

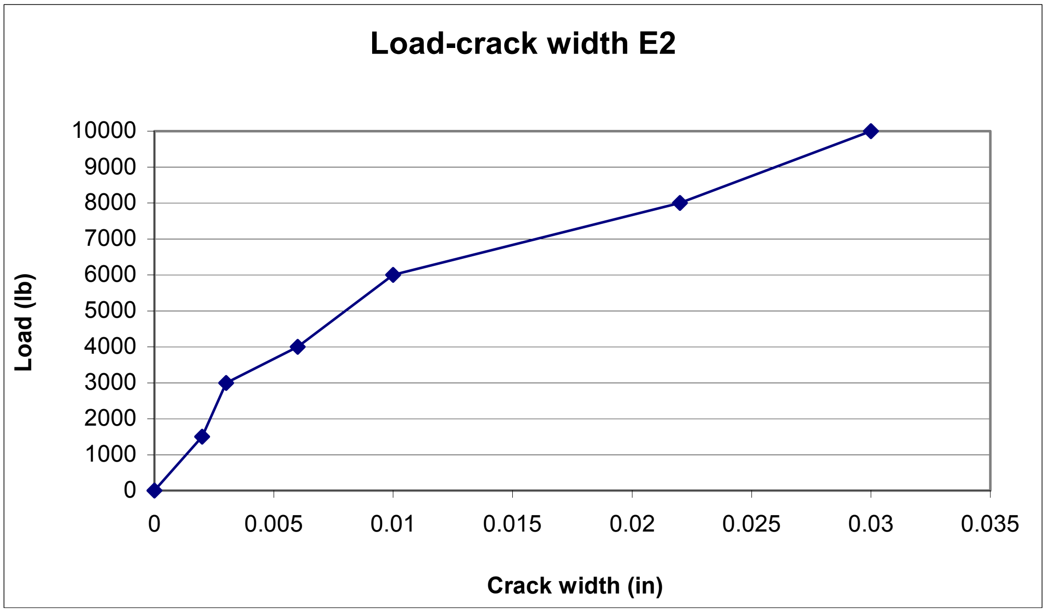

Fig D.3.5 Load-crack width curve of beam E2

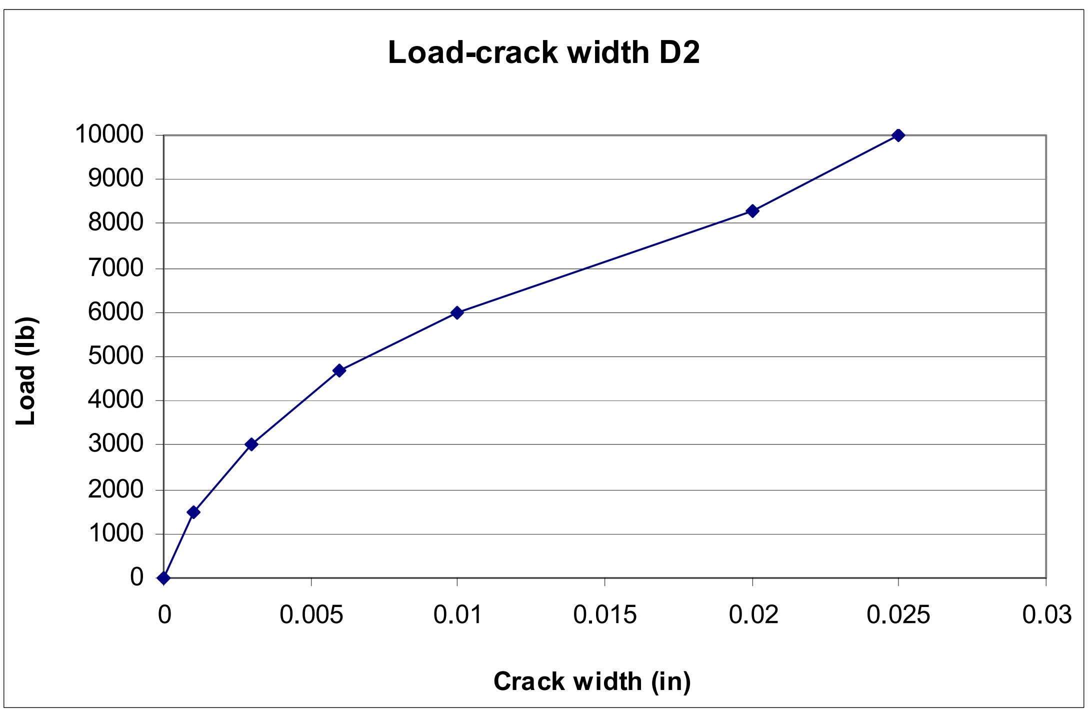

Fig D.3.6 Load-crack width curve of beam D2

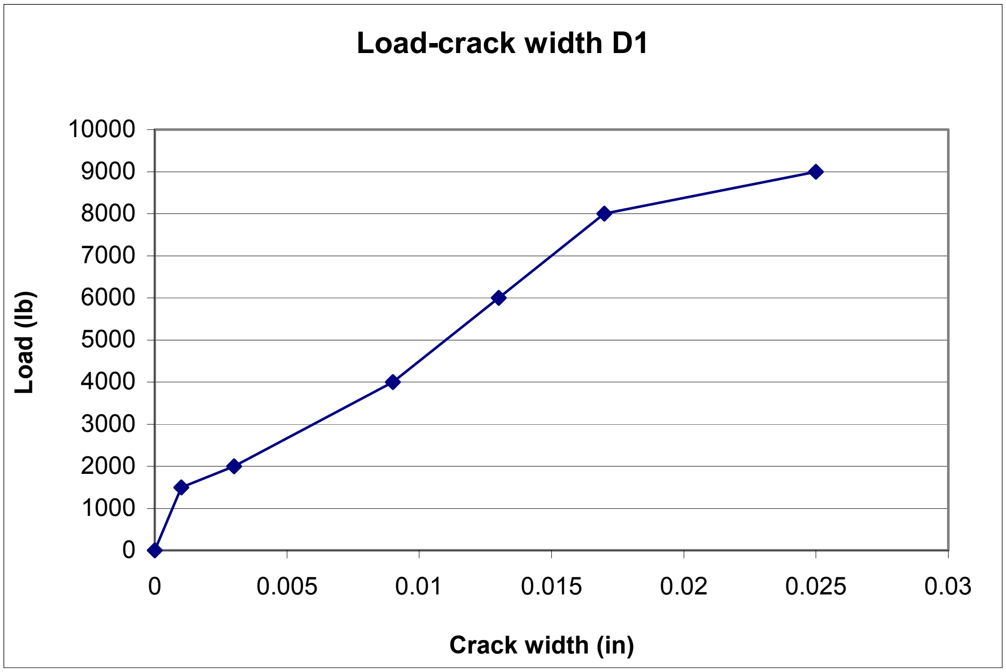

Fig D.3.7 Load-crack width curve of beam D1

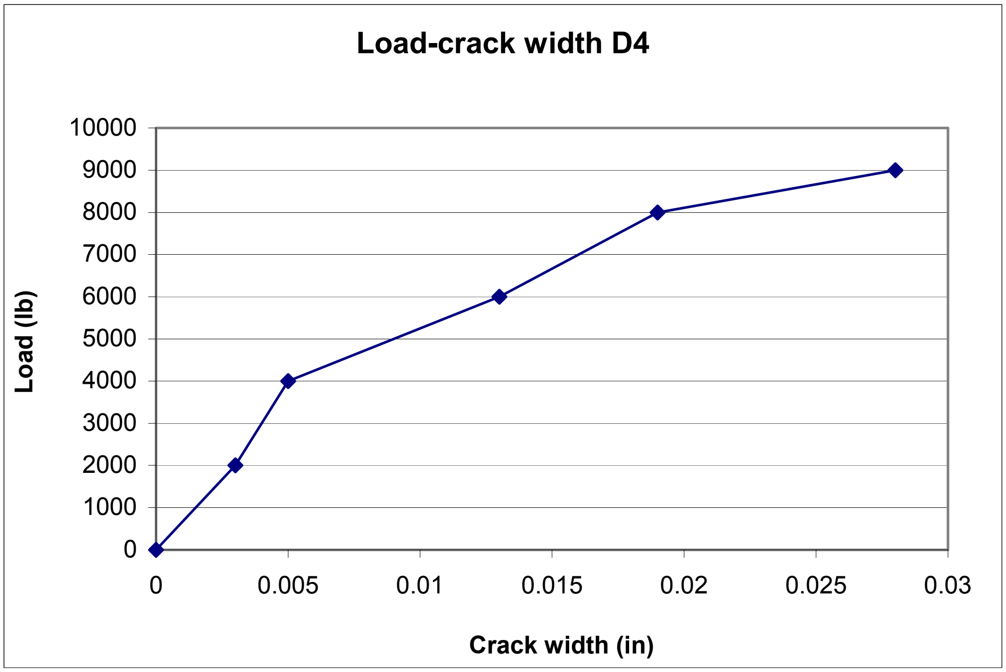

Fig D.3.8 Load-crack width curve of beam D4

Appendix E

LOAD-CRACK WIDTH DIAGRAMS OF BEAMS AGED IN ALKALINE AND SALT SOLUTIONS

E.1: Load-crack width diagram of beams aged in alkaline and salt solution at temperature

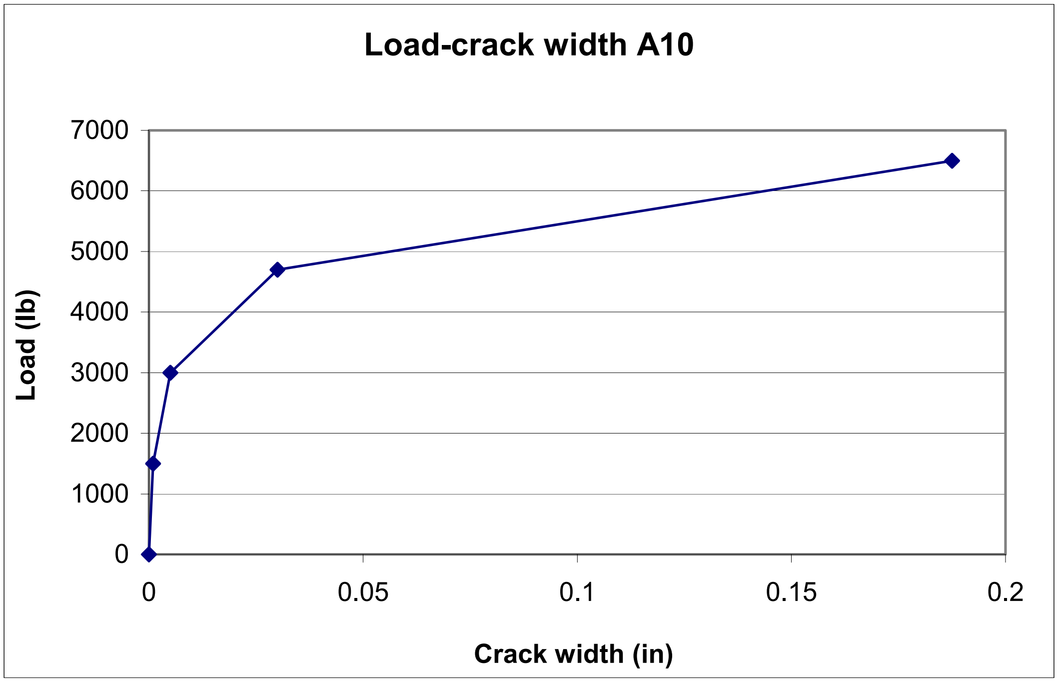

Fig E.1.1 Load-crack width curve of beam A10

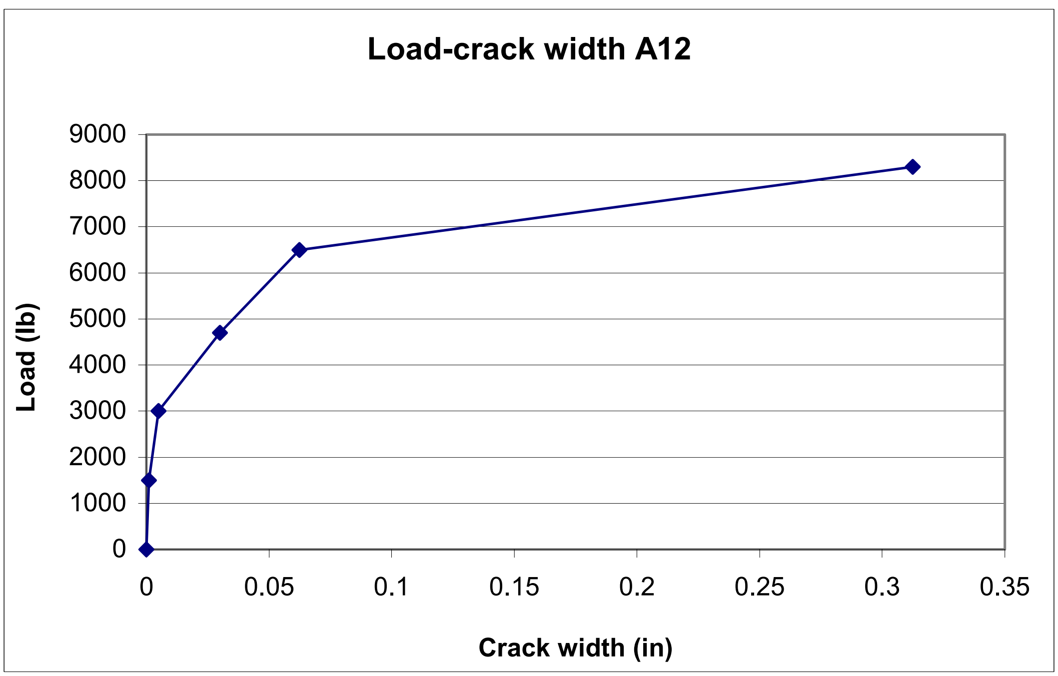

Fig E.1.2 Load-crack width curve of beam A12

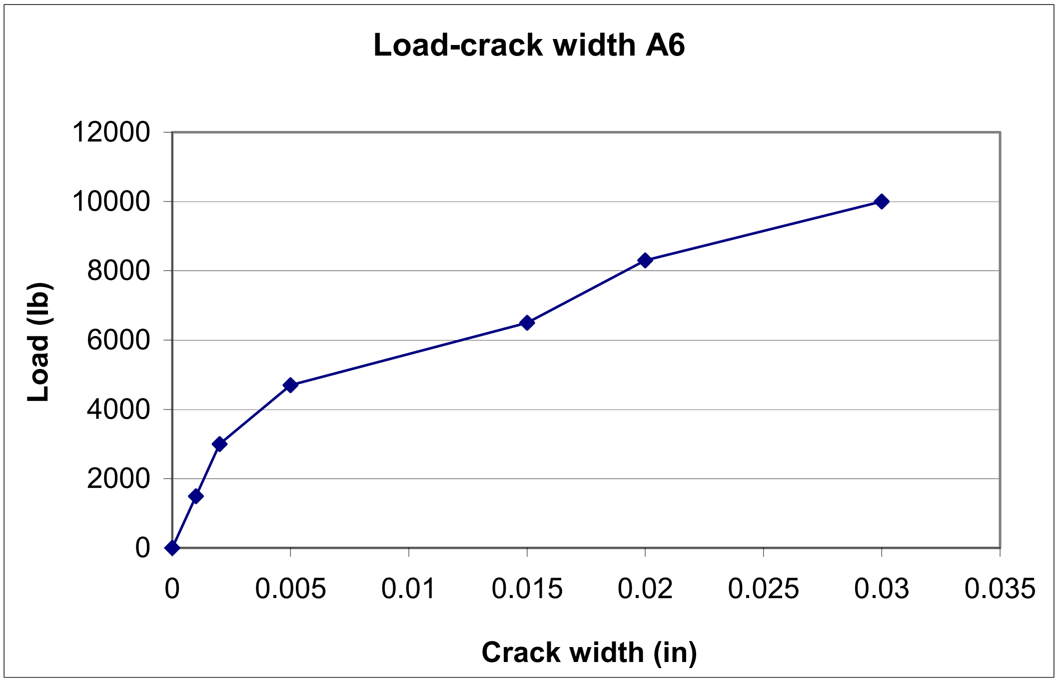

Fig E.1.3 Load-crack width curve of beam A6

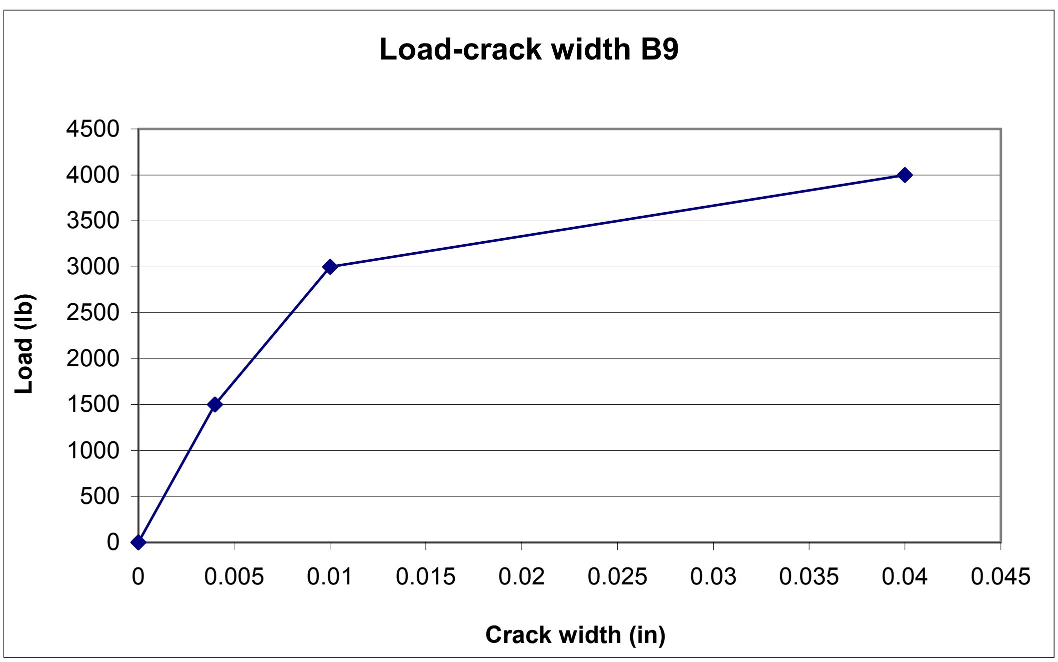

Fig E.1.4 Load-crack width curve of beam B9

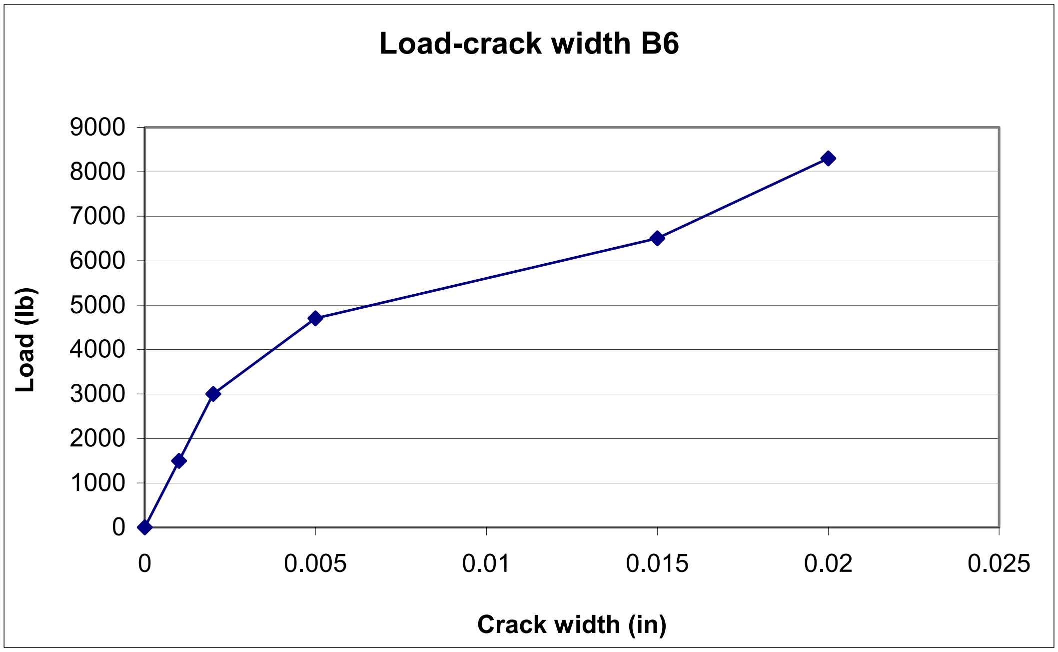

Fig E.1.5 Load-crack width curve of beam B6

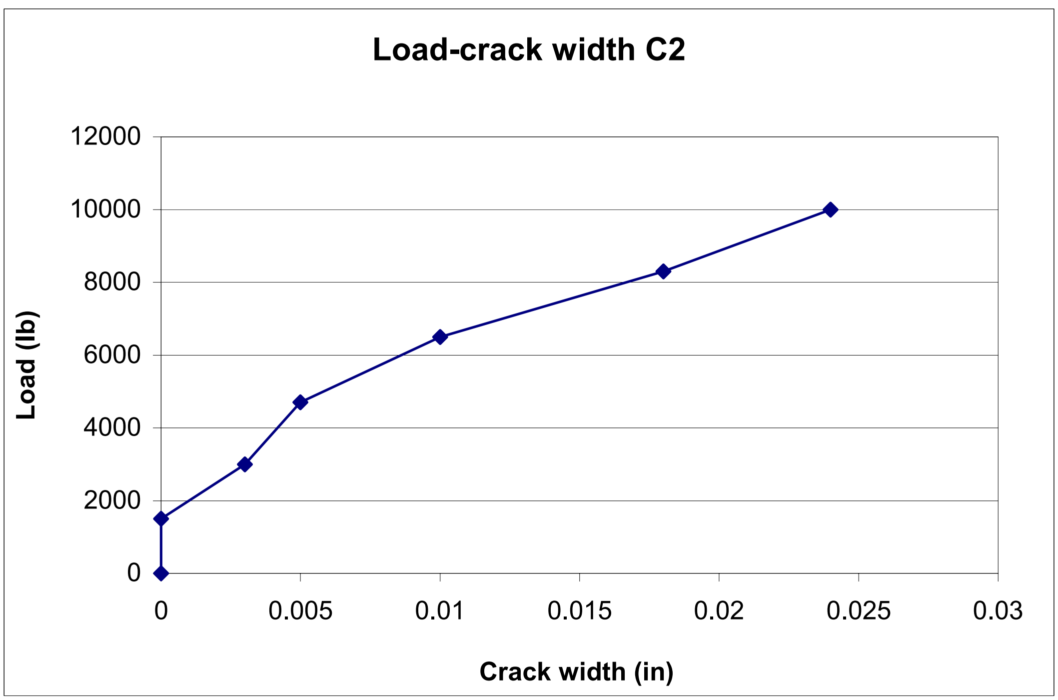

Fig E.1.6 Load-crack width curve of beam C2

E.2: Load-crack width diagram of beams aged in alkaline and salt solution under freeze-thaw conditioning.

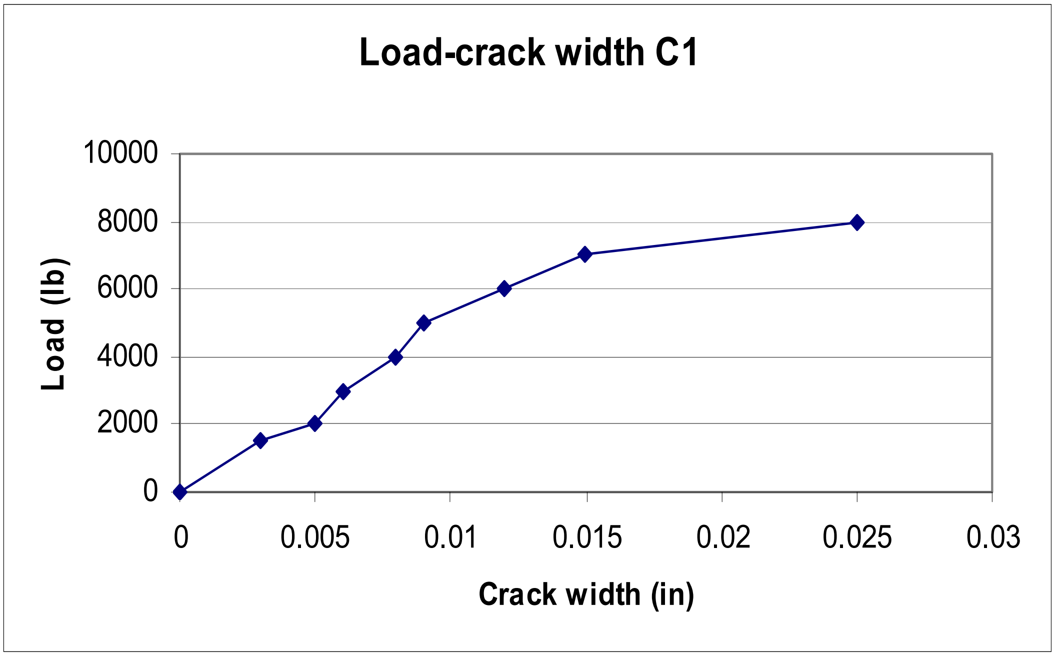

Fig E.2.1 Load-crack width curve of beam C1

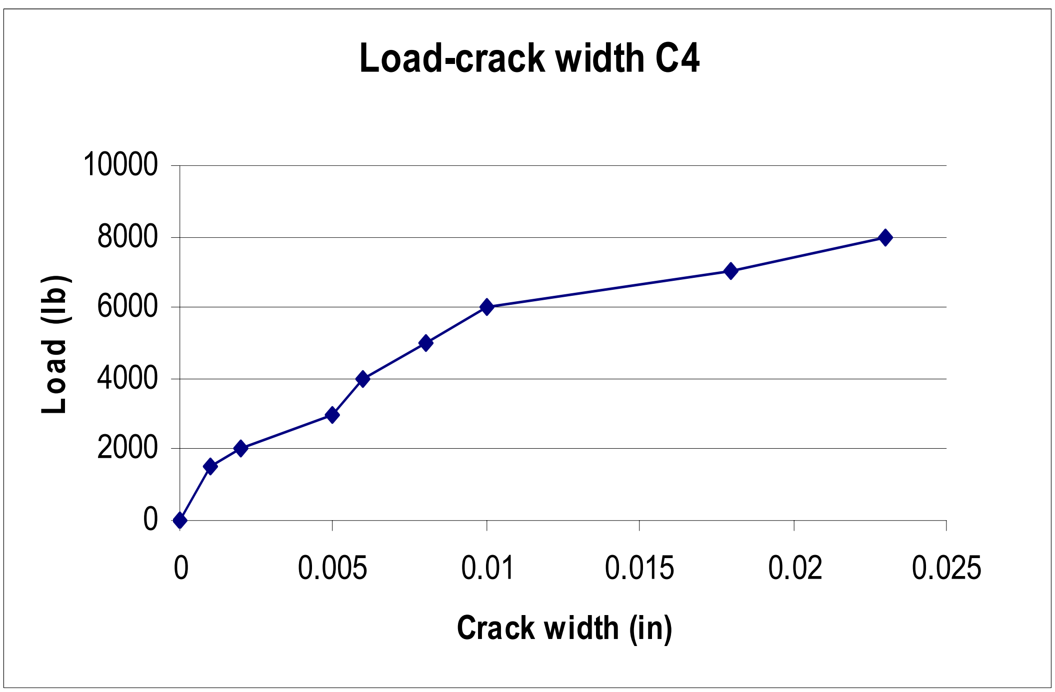

Fig E.2.2 Load-crack width curve of beam C4

Appendix F

STRESS-STRAIN DIAGRAMS OF STRIPS (WATER)

F.1: Stress-strain diagram of beams aged in water at room temperature

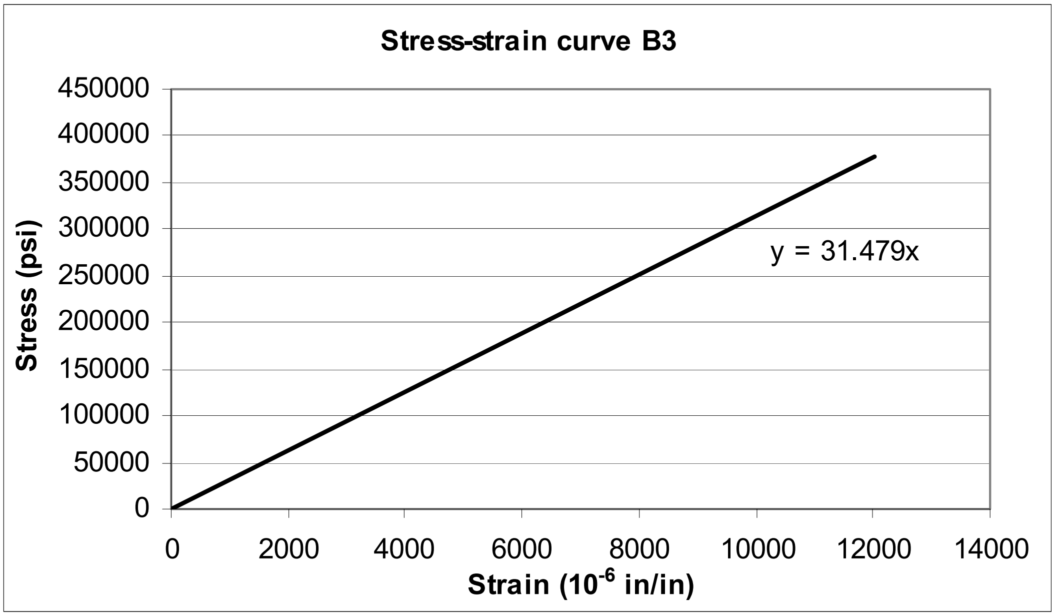

Fig F.1.1 Stress-strain curve of carbon fiber strip B3

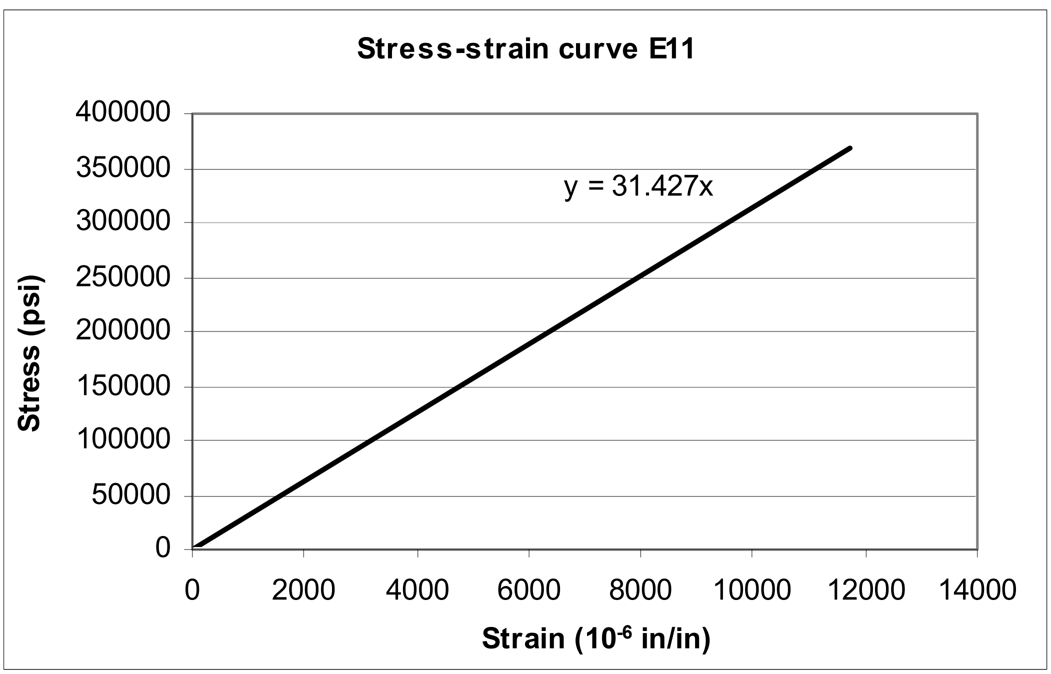

Fig F.1.2 Stress-strain curve of carbon fiber strip E11

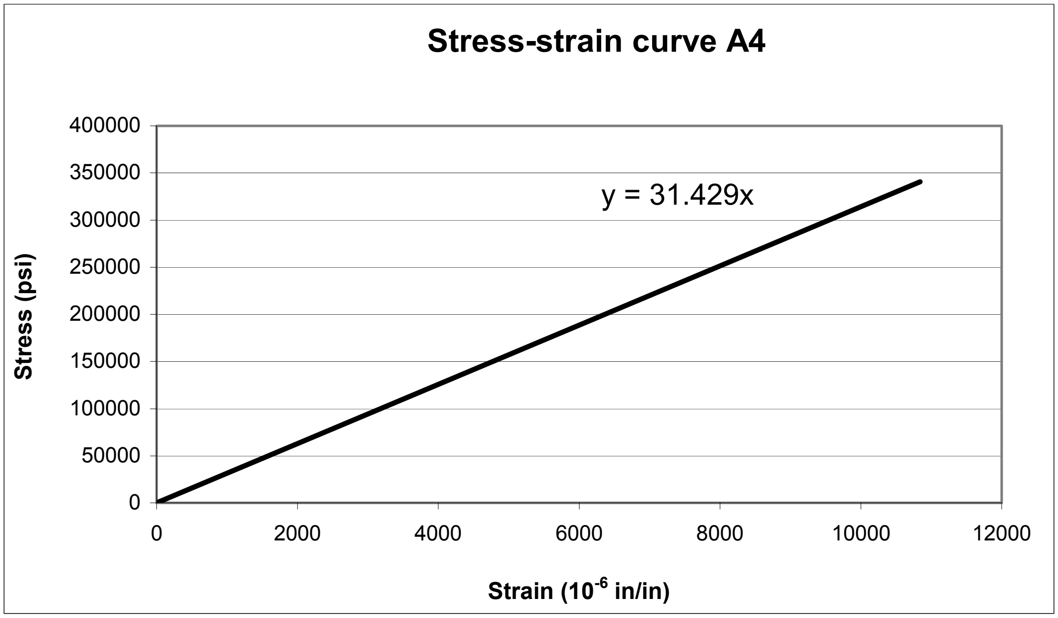

Fig F.1.3 Stress-strain curve of carbon fiber strip A4

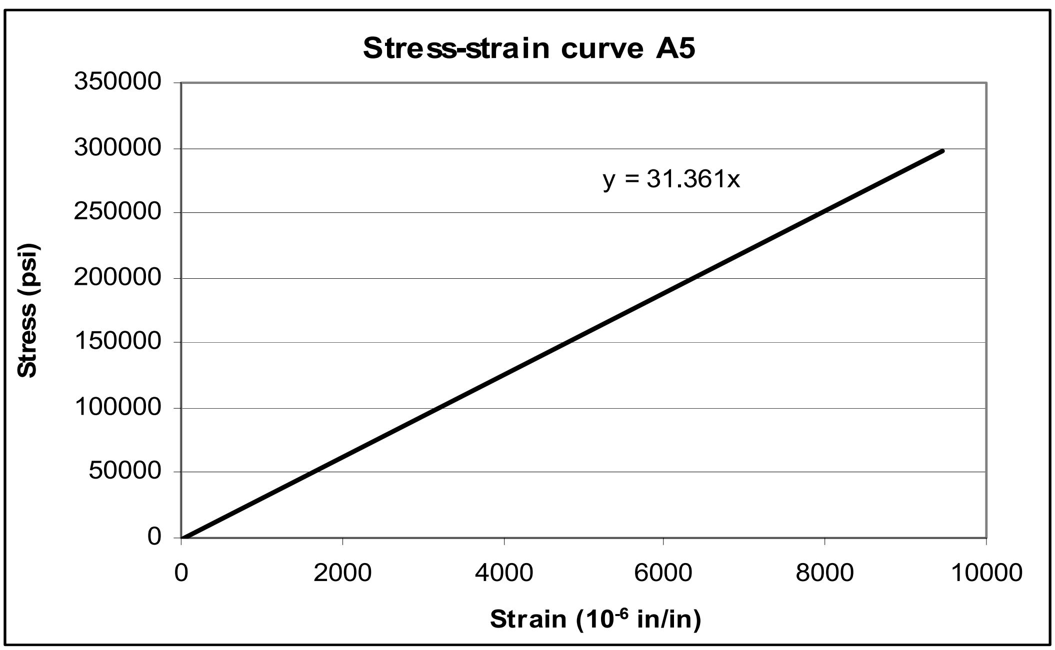

Fig F.1.4 Stress-strain curve of carbon fiber strip A5

F.2: Stress-strain diagram of beams aged in water at 110 °F temperature

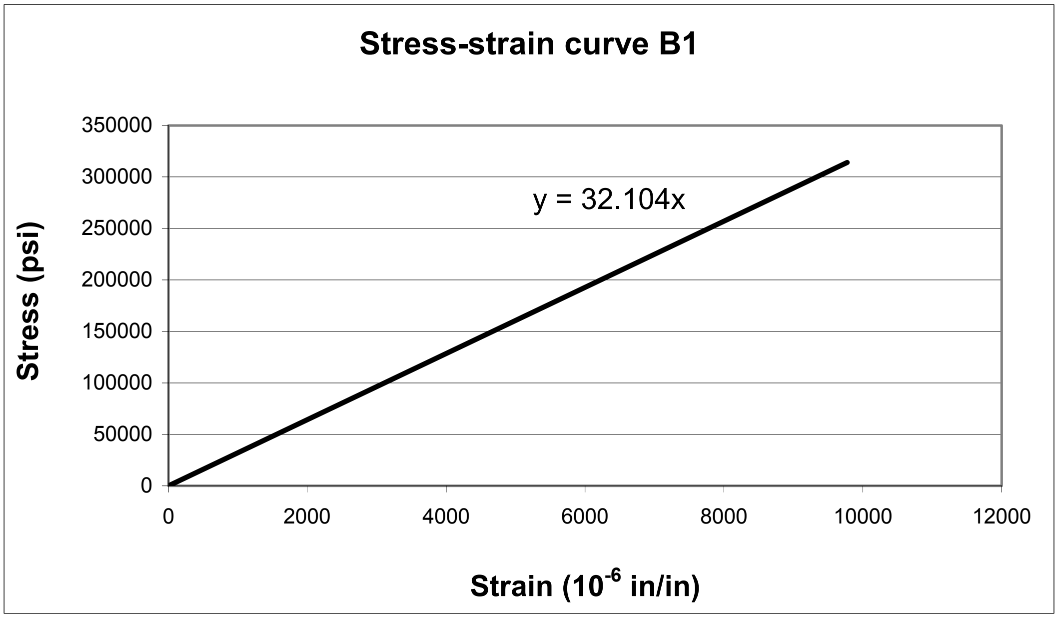

Fig F.2.1 Stress-strain curve of carbon fiber strip B1

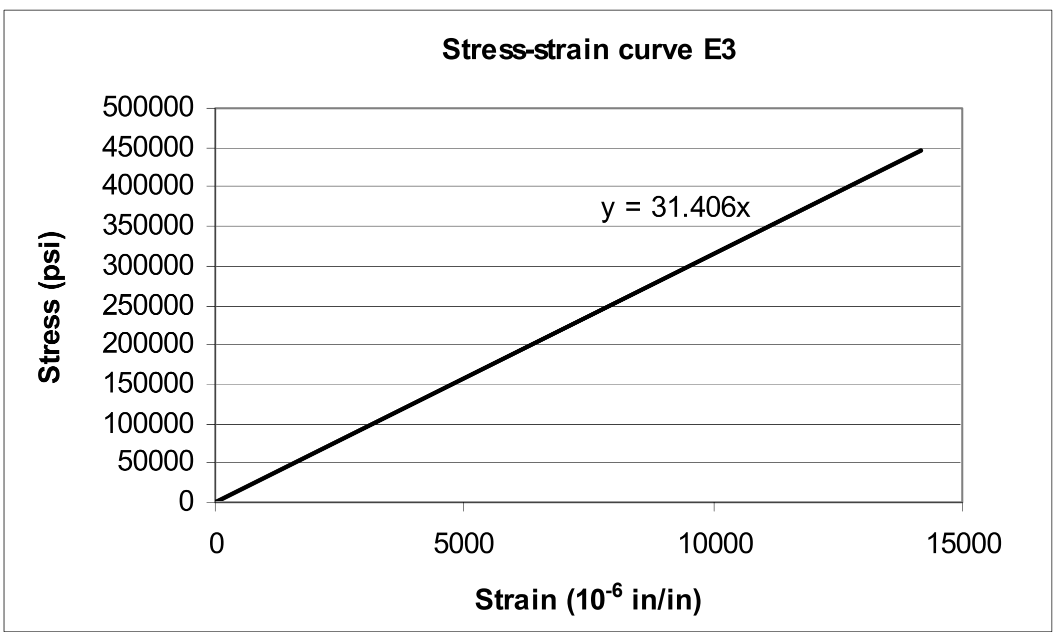

Fig F.2.2 Stress-strain curve of carbon fiber strip E3

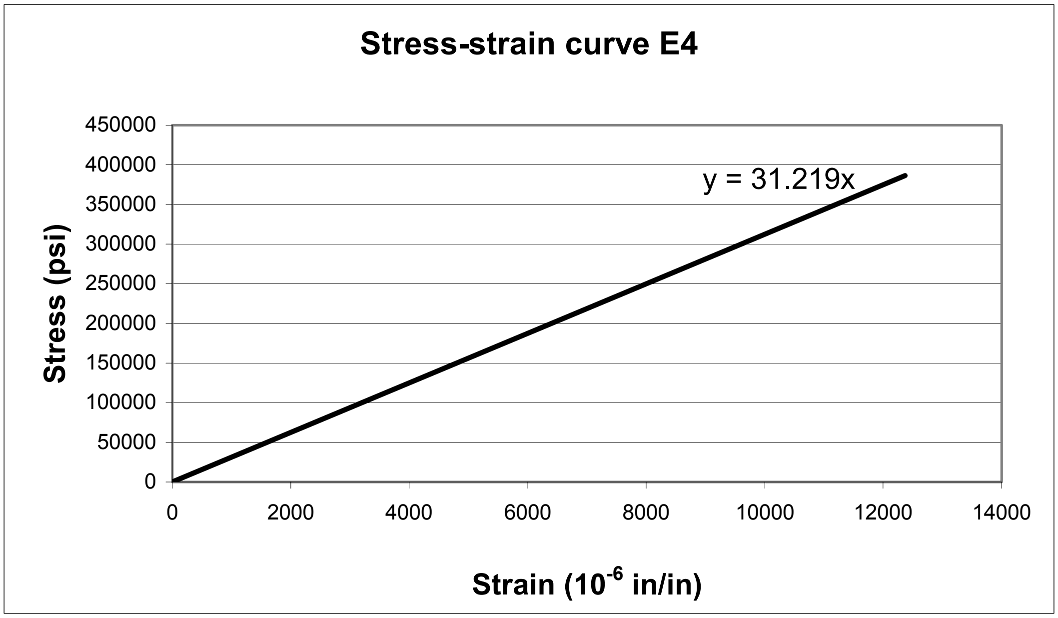

Fig F.2.3 Stress-strain curve of carbon fiber strip E4

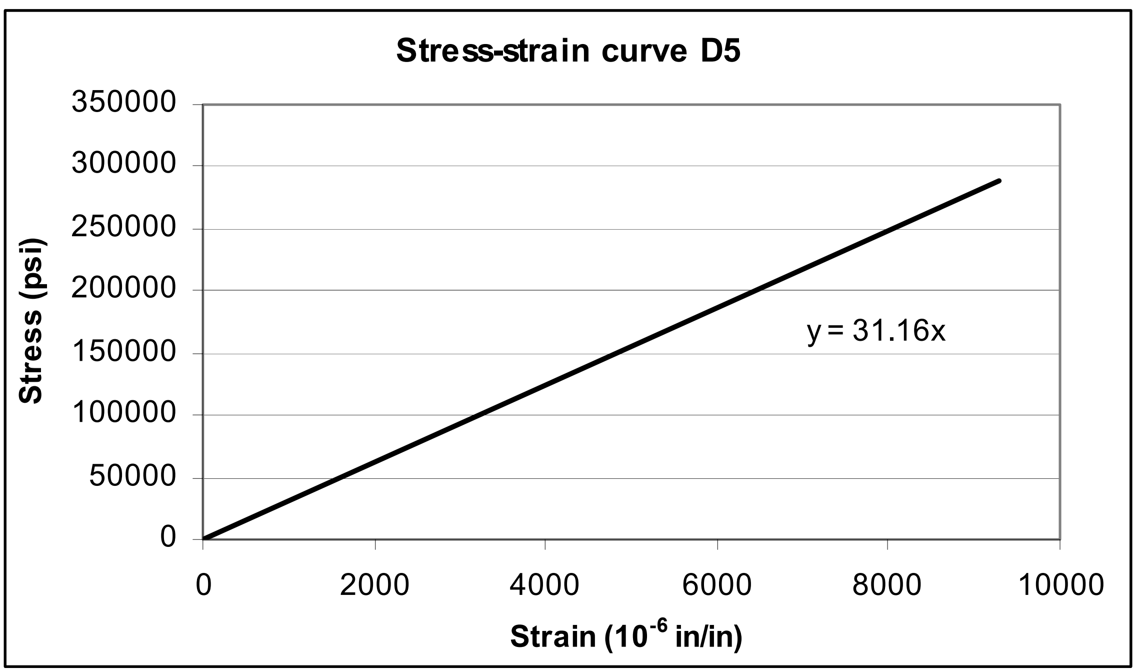

Fig F.2.4 Stress-strain curve of carbon fiber strip D5

F.3: Stress-strain diagram of beams aged in water at 140 °F temperature

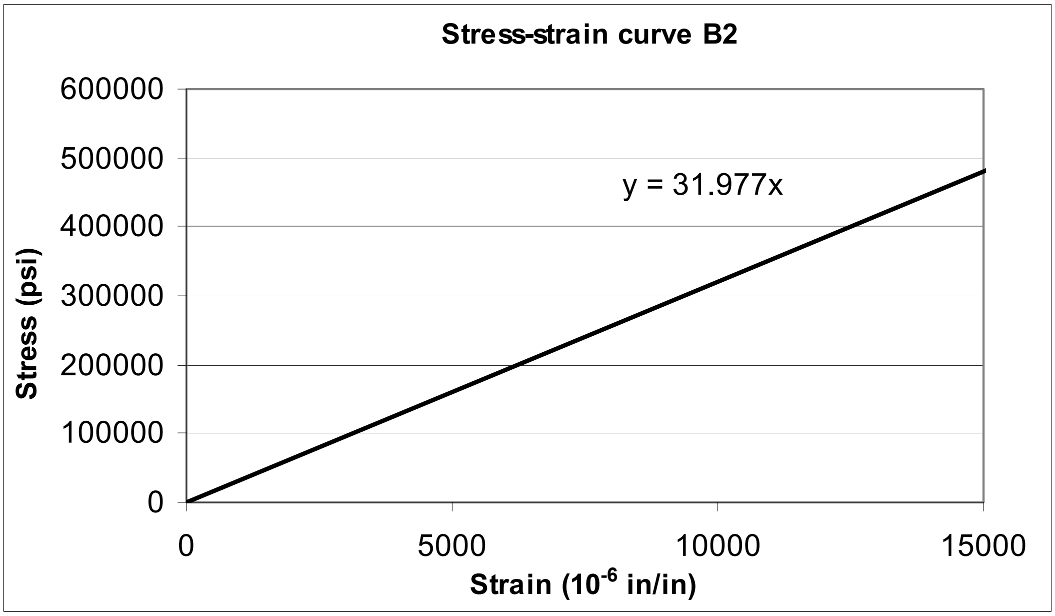

Fig F.3.1 Stress-strain curve of carbon fiber strip B2

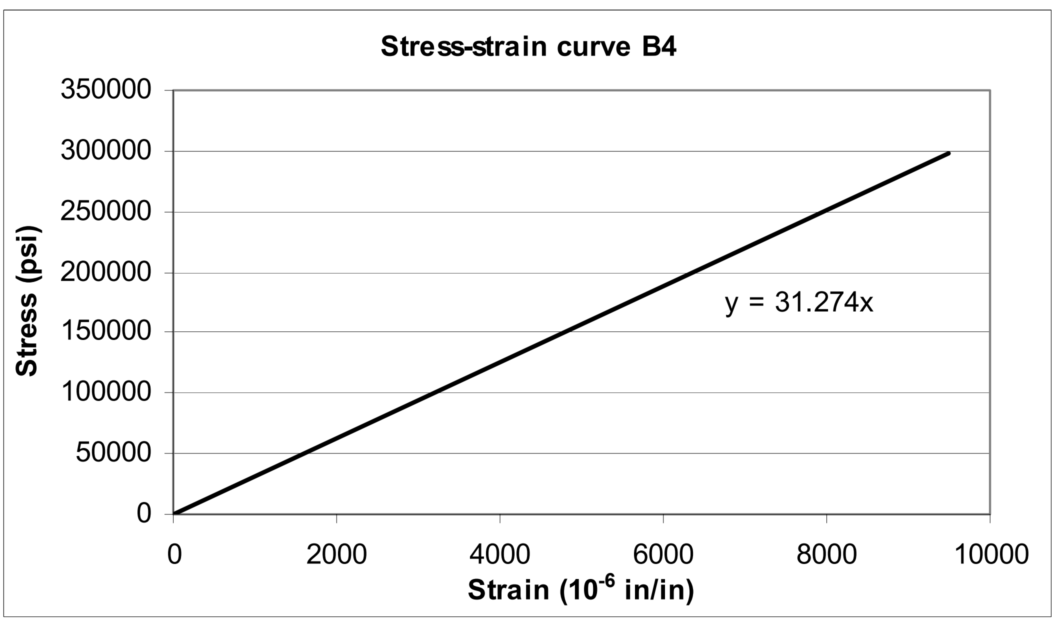

Fig F.3.2 Stress-strain curve of carbon fiber strip B4

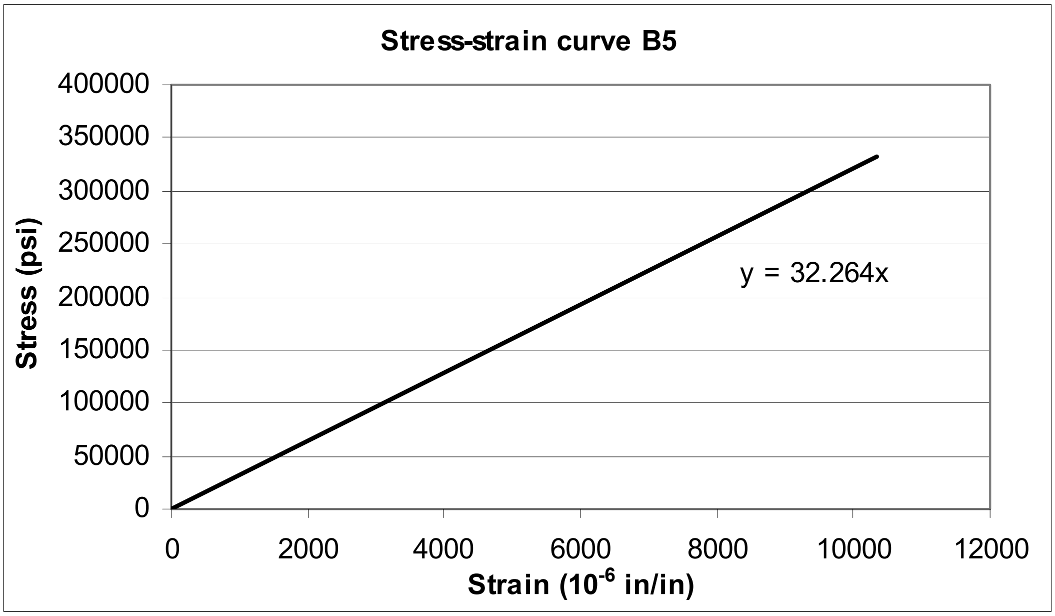

Fig F.3.3 Stress-strain curve of carbon fiber strip B5

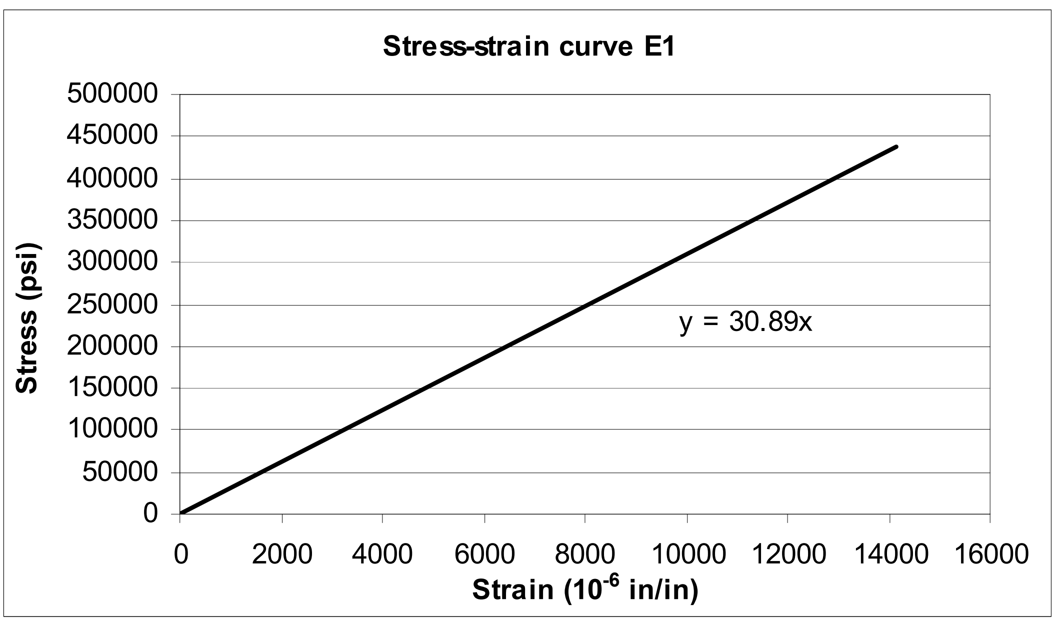

Fig F.3.4 Stress-strain curve of carbon fiber strip E1

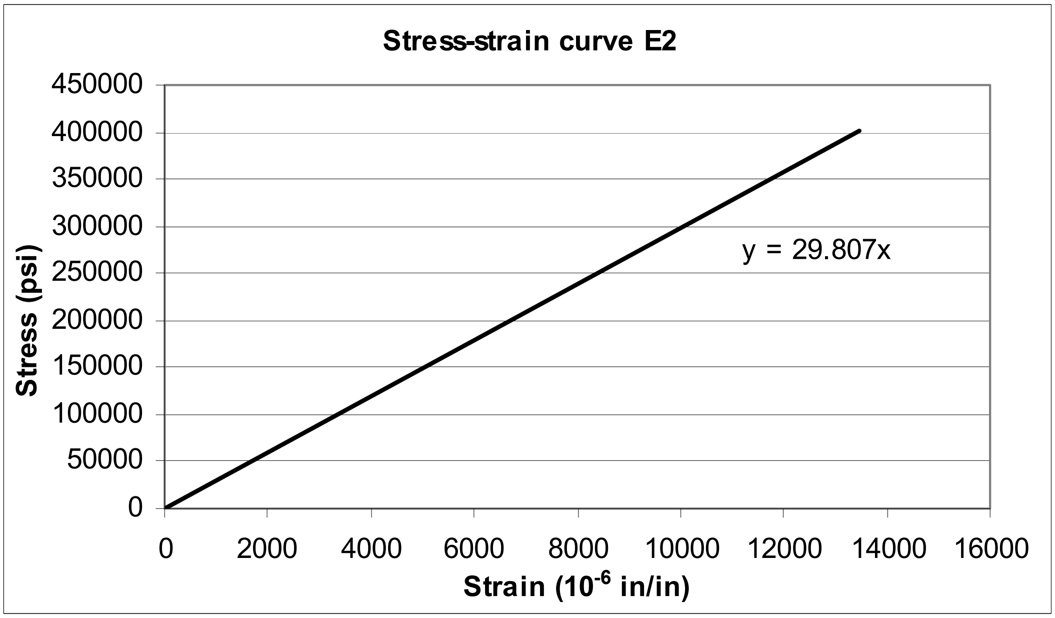

Fig F.3.5 Stress-strain curve of carbon fiber strip E2

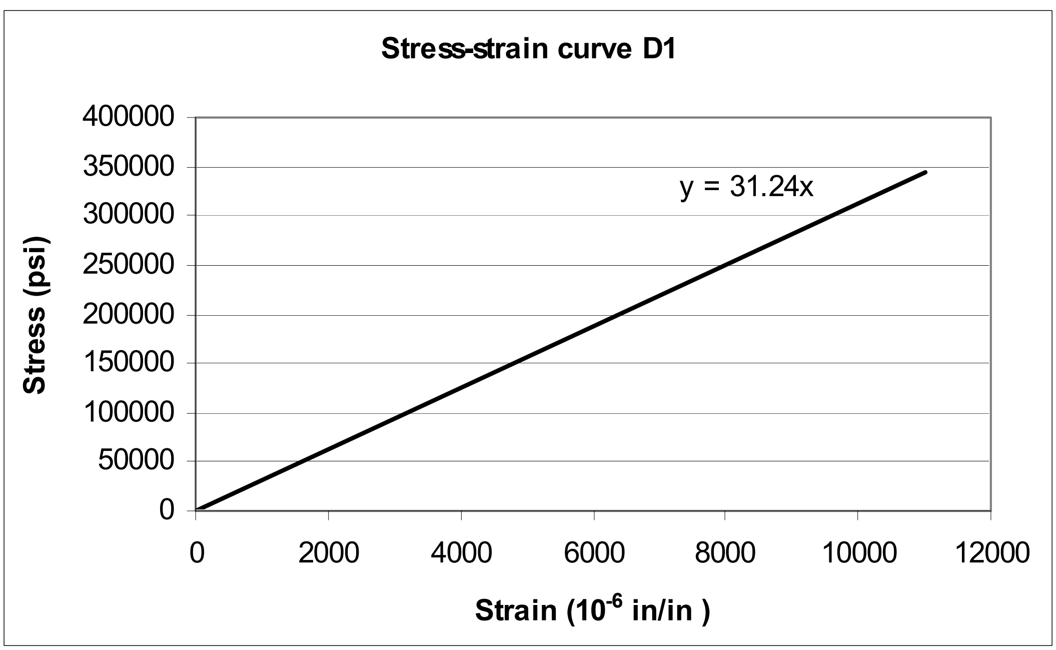

Fig F.3.6 Stress-strain curve of carbon fiber strip D1

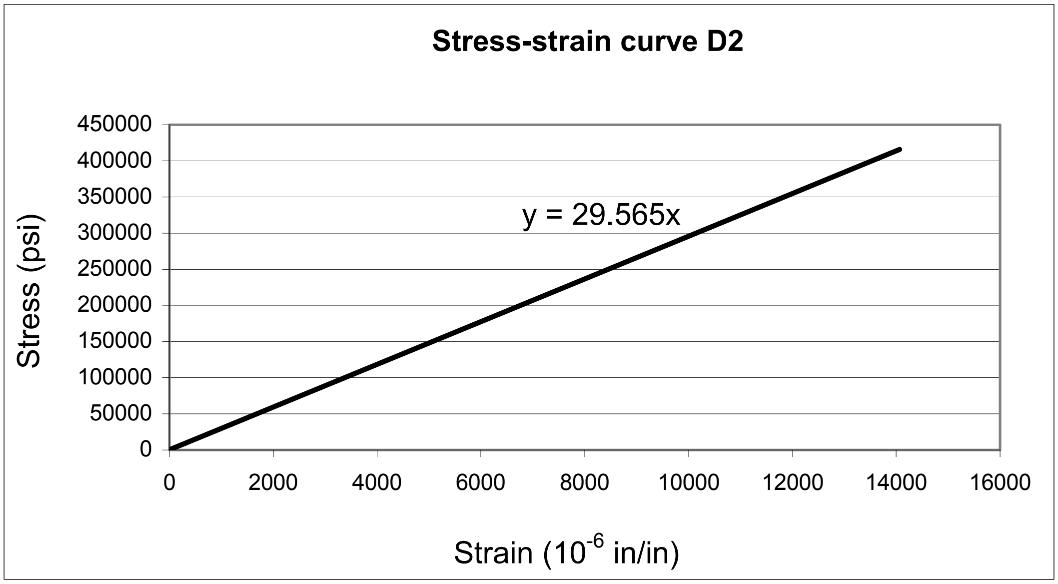

Fig F.3.7 Stress-strain curve of carbon fiber strip D2

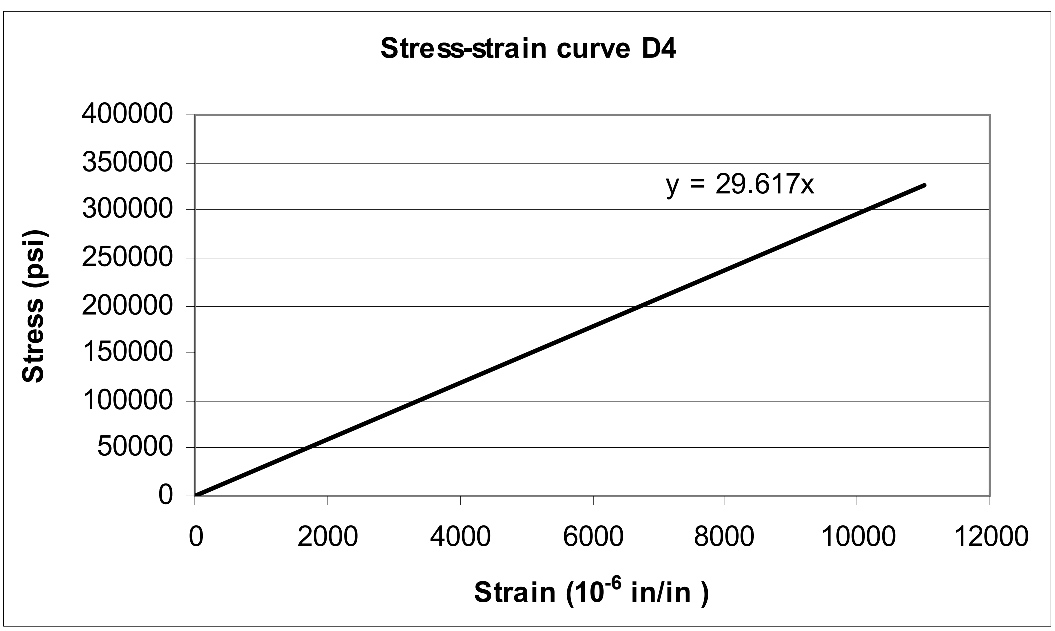

Fig F.3.8 Stress-strain curve of carbon fiber strip D4

Appendix G

STRESS-STRAIN DIAGRAMS OF STRIPS

(ALKALINE AND SALT SOLUTIONS)

G.1: Stress-strain diagram of beams aged in alkaline and salt solution at room temperature

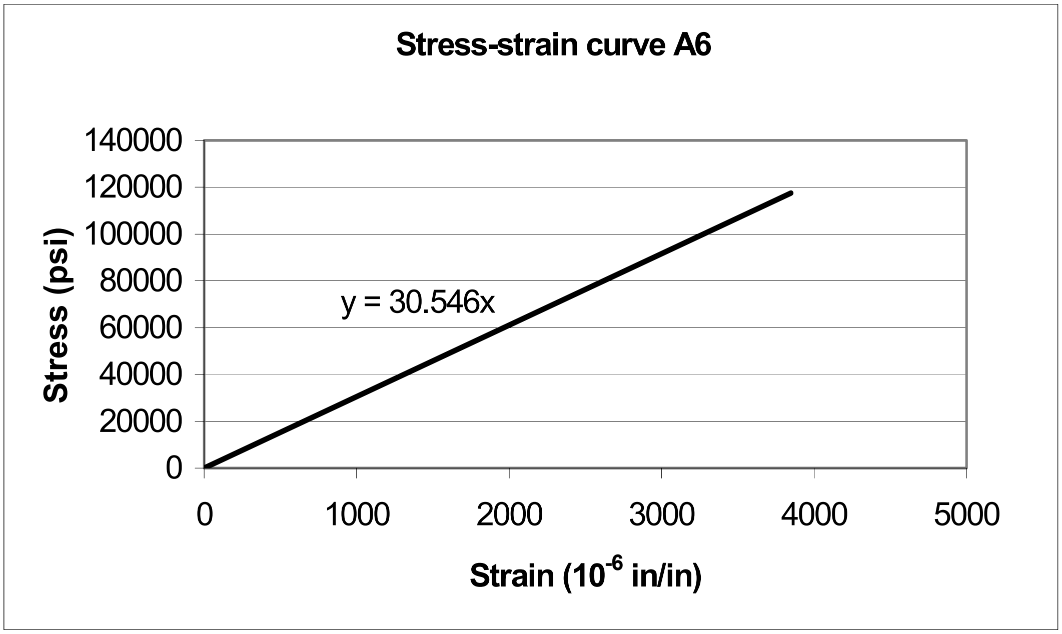

Fig G.1.1 Stress-strain curve of carbon fiber strip A6

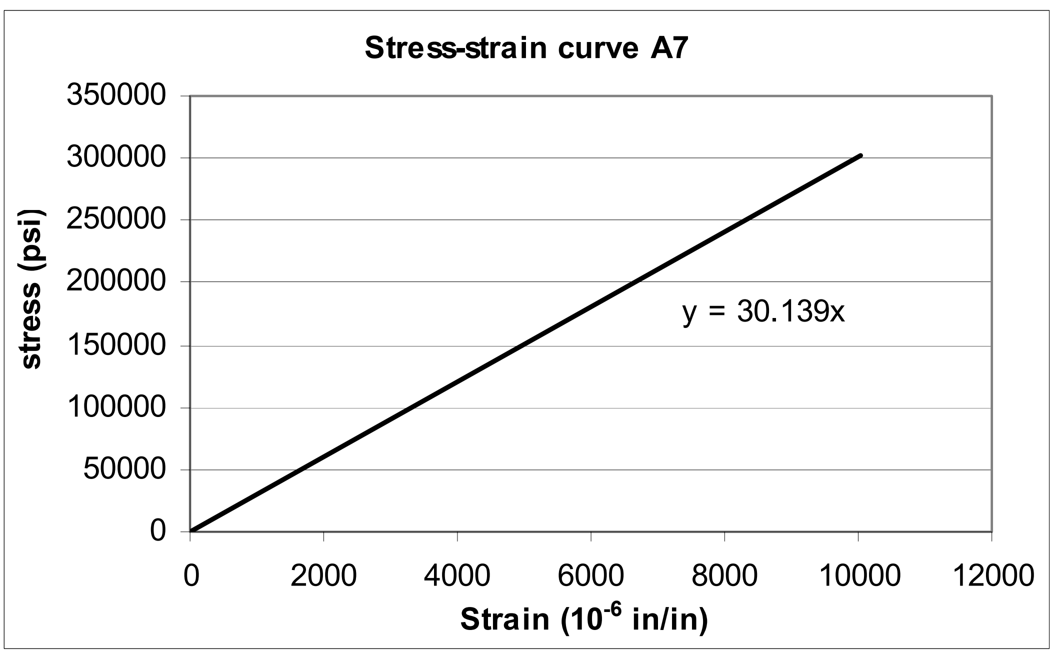

Fig G.1.2 Stress-strain curve of carbon fiber strip A7

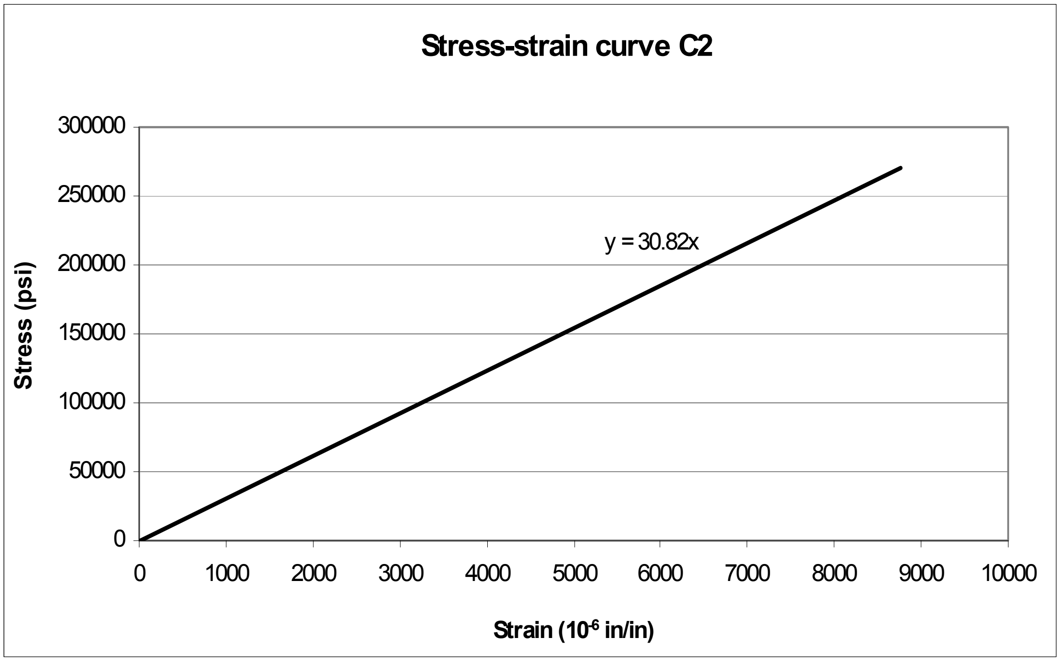

Fig G.1.3 Stress-strain curve of carbon fiber strip C2

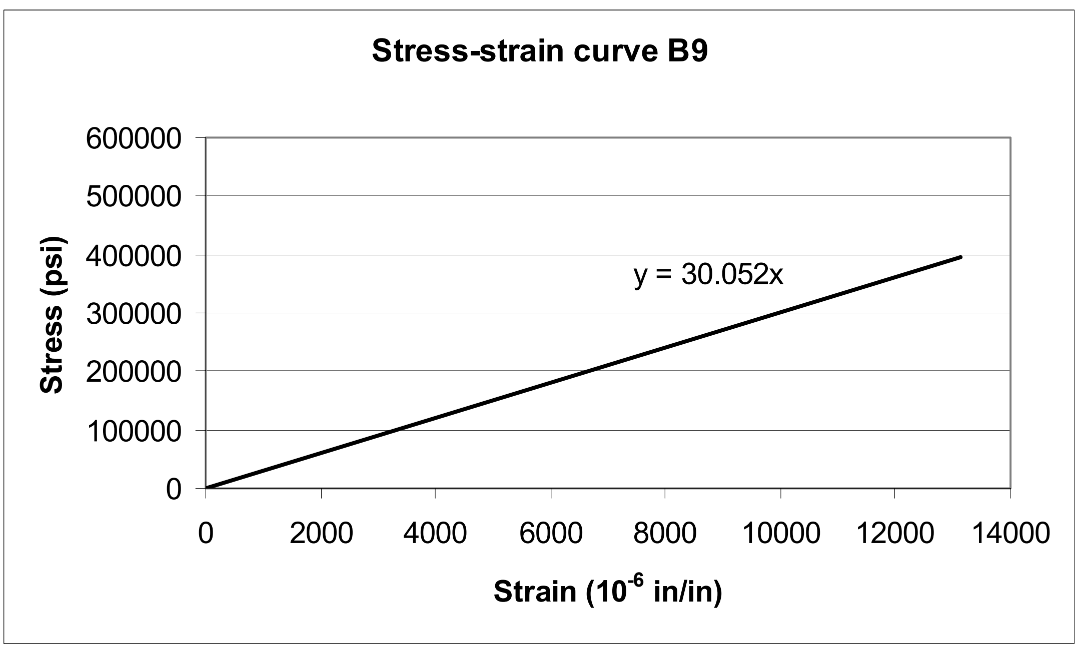

Fig G.1.4 Stress-strain curve of carbon fiber strip B9

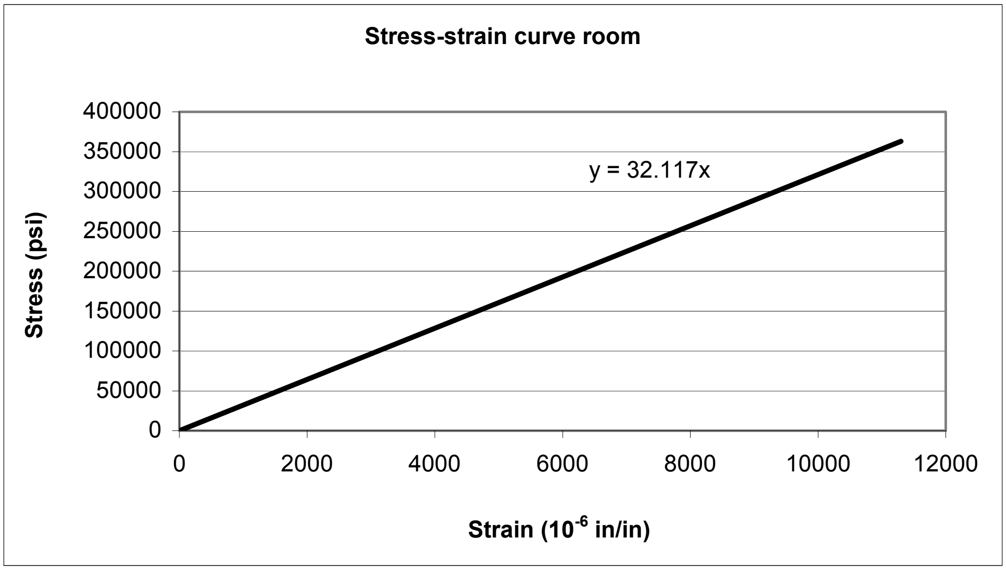

Fig G.1.5 Stress-strain curve of carbon fiber strip (new)

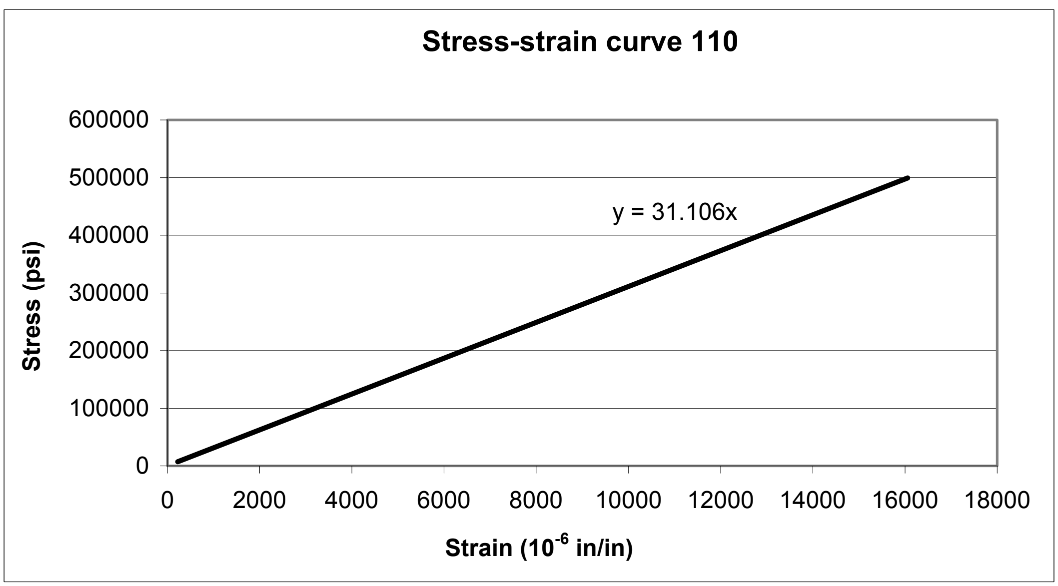

Fig G.1.6 Stress-strain curve of carbon fiber strip 110 (new)

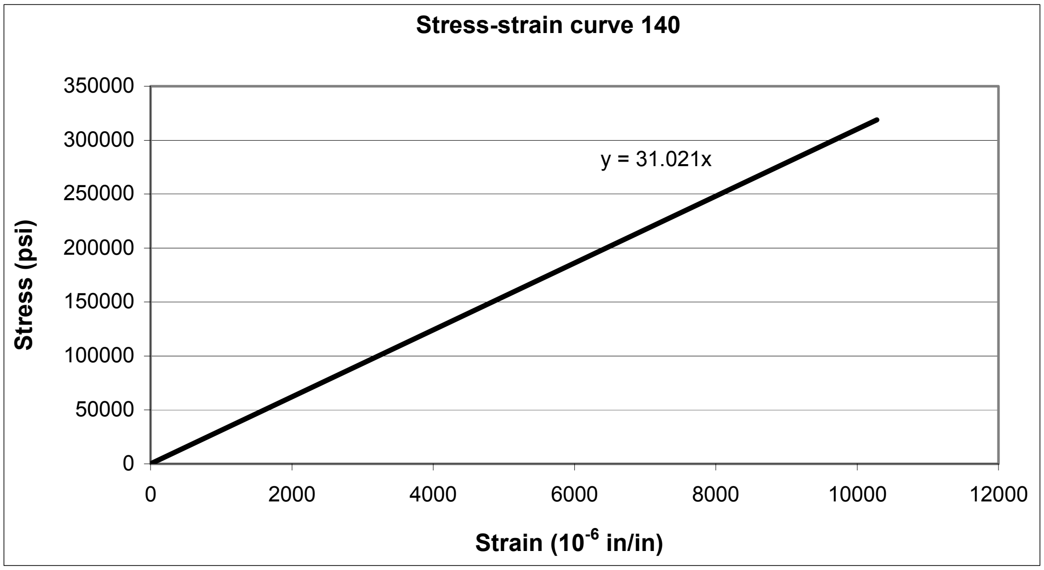

Fig G.1.7 Stress-strain curve of carbon fiber strip 140 (new)

G.2: Stress-strain diagram of beams aged in alkaline and salt solution at freeze-thaw conditioning

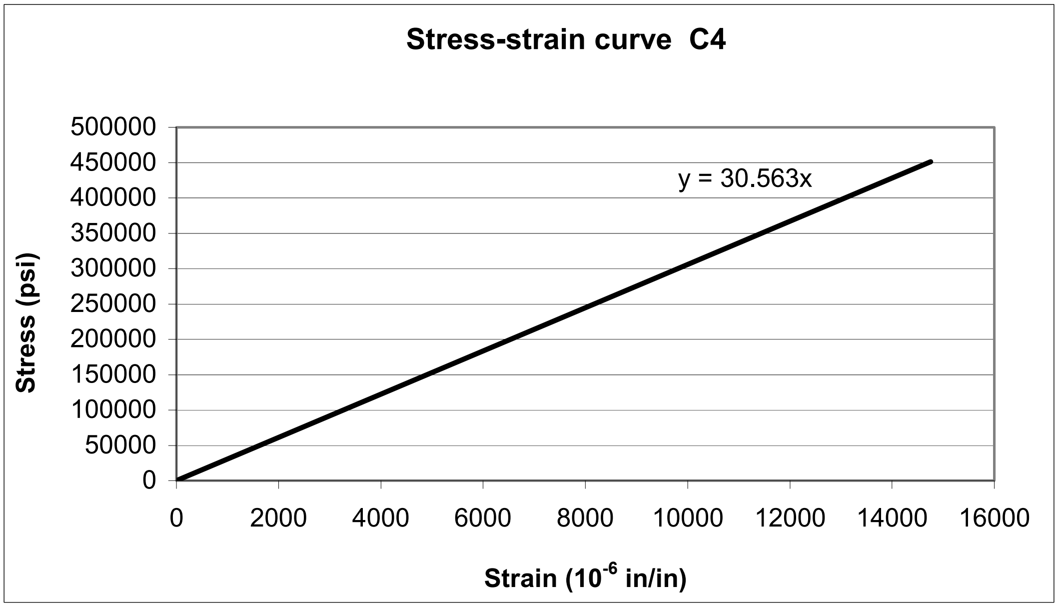

Fig G.2.1 Stress-strain curve of carbon fiber strip C4

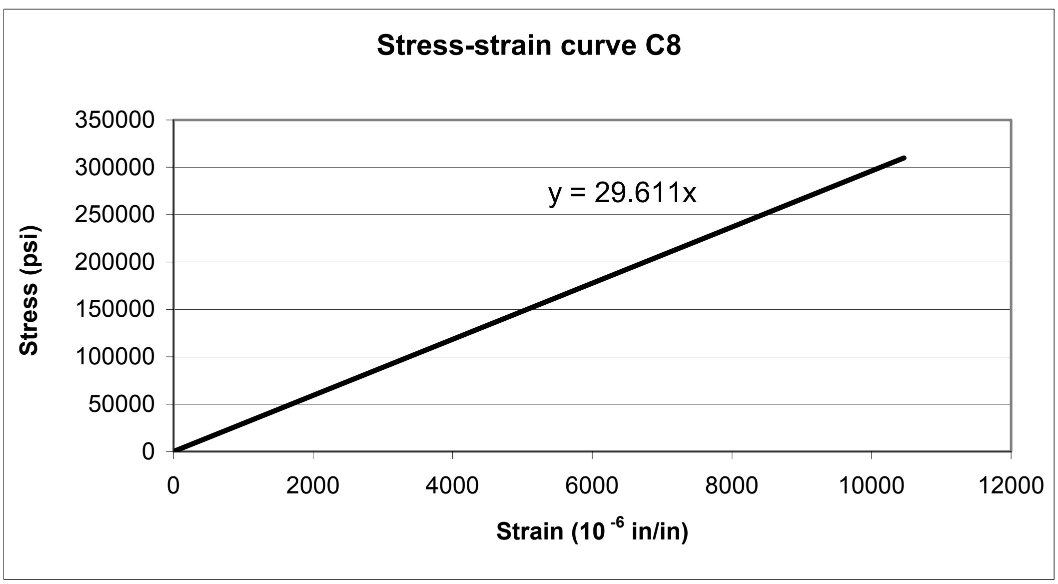

Fig G.2.2 Stress-strain curve of carbon fiber strip C8

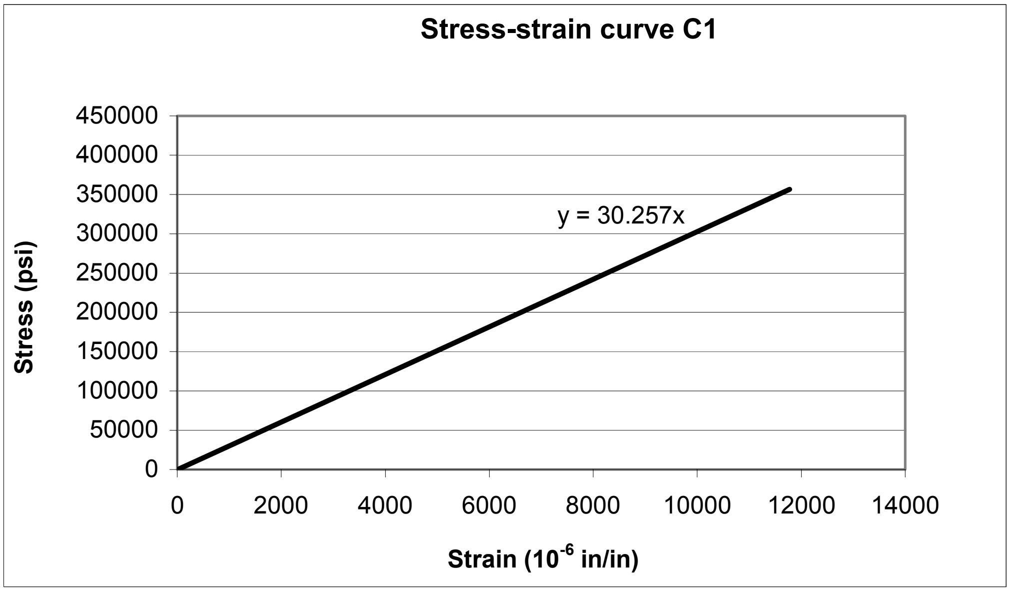

Fig G.2.3 Stress-strain curve of carbon fiber strip C1

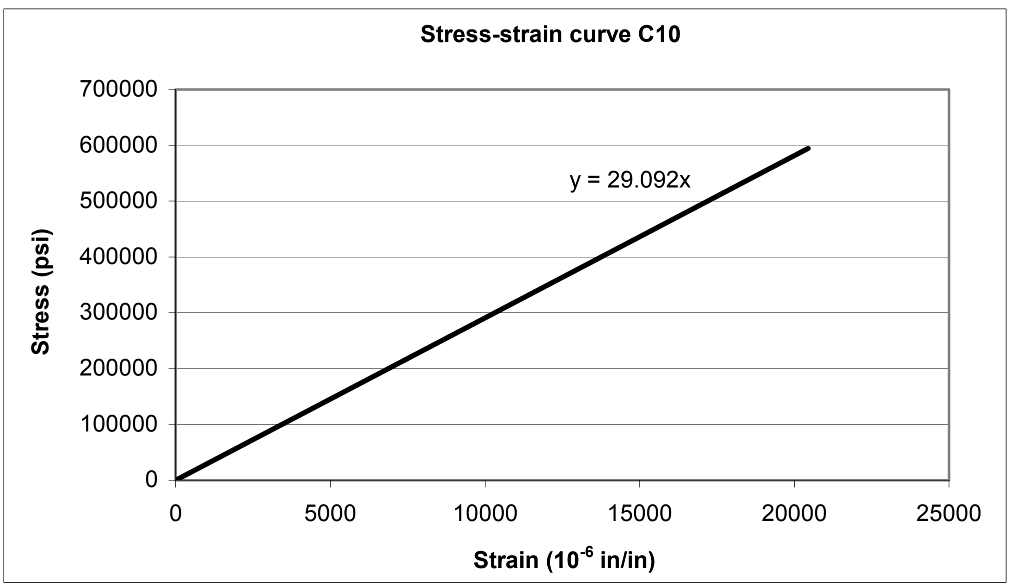

Fig G.2.4 Stress-strain curve of carbon fiber strip C10

Appendix H

STRESS-STRAIN DIAGRAMS OF STRIPS (OUTSIDE WEATHERING)

Appendix H.1: Stress-strain diagram of beams aged naturally outside

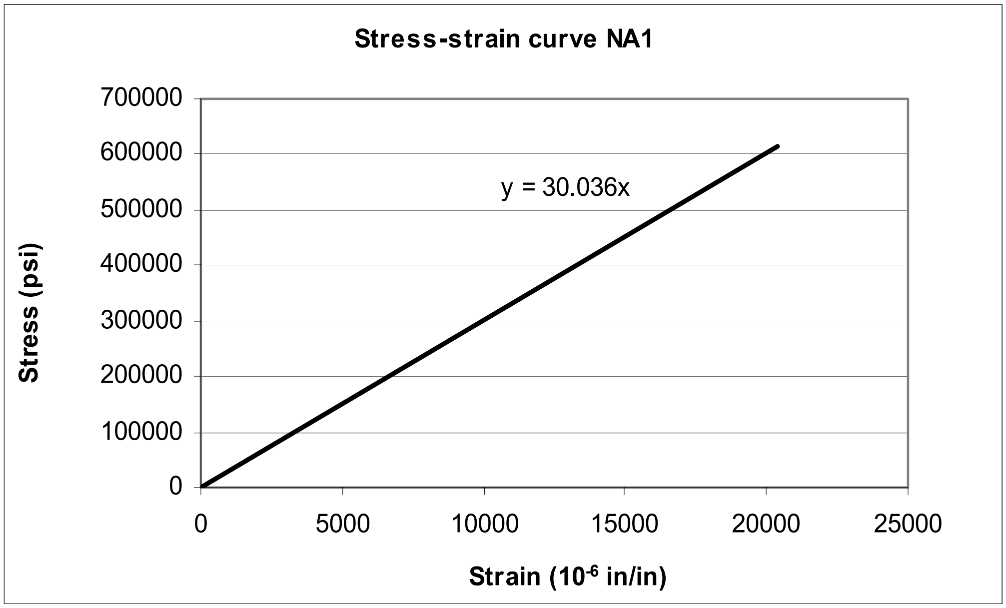

Fig H.1.1 Stress-strain curve of carbon fiber strip NA1

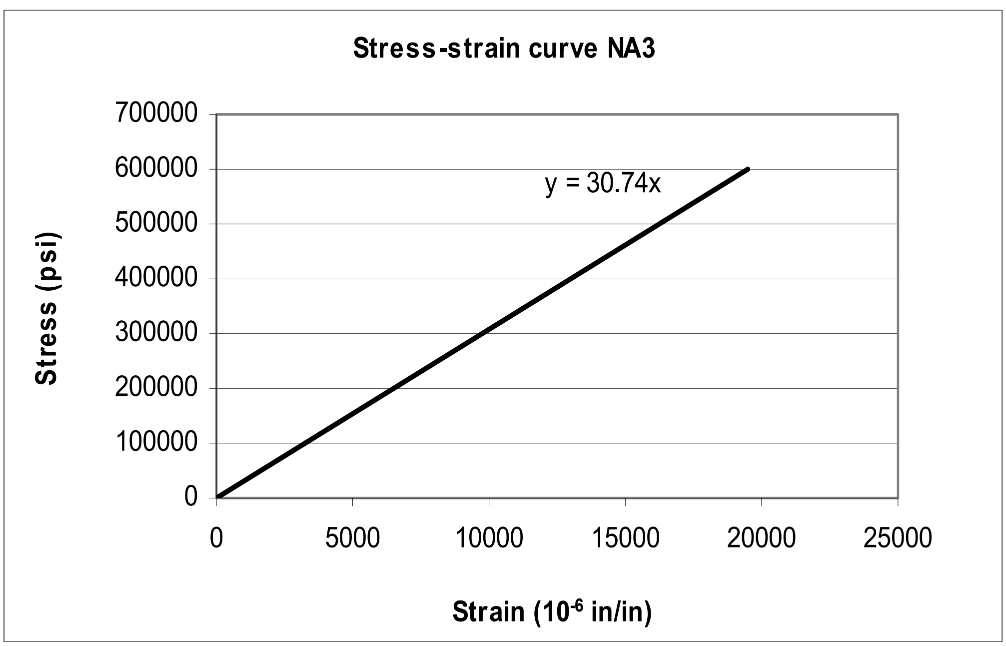

Fig H.1.2 Stress-strain curve of carbon fiber strip NA3

Appendix I

TABLE AND DIAGRAMS FROM NON-WRAPPED CONCRETE BEAMS

Table I-1 Three-point bending test results for non-wrapped beams

Age (month)	Temp (F)	Beam	Wrap* Type	Max load (recorded) (kips)	Max. Moment (recorded) (kip-ft)	Max deflection (recorded) (in)	Max crack-width (recorded) (in)
3	room	Non aged 1	Without wrap	6.11	6.36	0.754	0.022
		Non aged 2		5.87	6.12	0.833	0.021

RESISTING MOMENT CALCULATION

Resisting moment of non-wrapped concrete beam

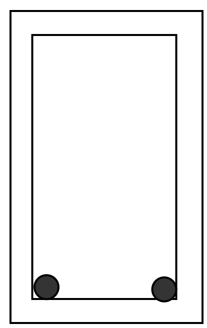

Fig I.1 non- wrapped concrete beams cross section

Dimension: b= 5 inch

h= 8 inch

d= 6 inch

d'=2 inch

Reinforcement: Tension = 2#3 bars

Compression = Nominal

Shear = Adequate

Given: $f'_c = 4$ ksi

$f_y = 60$ksi

$A_s = 0.22$ in2

$A'_s =$ Neglible

Solution: Determine whether the beam will fail in compression or tension failure by comparing ρ of the beam with balanced reinforcement condition ρ_b.

From equilibrium: compression = tension

$A_s f_y = 0.85 f_c' ab$

$\rho = (0.85\beta_1 f_c' / f_y) \times (0.003 / (0.003 + \varepsilon_s))$

At balanced condition: $\varepsilon_s = 0.003$

$f'_c = 4$ ksi

$\beta_1 = 0.85$

$\rho_b = (0.85 \times 0.85 \times 4 / 60) \times (0.003 / (0.003 + 0.00207))$

$\rho_b = 0.0285$

Calculate ρ of beam:

$\rho = A_s / (bd) = 0.22/(5 \times 6) = 0.00733$

Commentary: Since ρ of the beam is significantly less than that required for balanced failure. Then, this beam can be assumed in tension failure.

From equilibrium: compression = tension

$$C_{concrete} = T_{steel}$$

$$0.85 f_c' ab = A_s f_s$$

Assume Tension failure $f_s = f_y$ and $a = \beta_1 c$

$0.85 \times 0.85 \times 4 \times c \times 5 = (0.22 \times 60)$

$c = 0.913$ inch and $a = 0.776$ inch

Check for strain compatibility:

$\varepsilon_s = 0.003 \times (6-0.913)/0.913 = 0.01672$

$\varepsilon_s > \varepsilon_y$ (0.00207) then $f_s = f_y$

Capacity of resisting moment for non-wrapped concrete beam

$M_n = A_s f_y (d-0.5a))$

$=[0.22 \times 60 \times (6 - (0.5 \times 0.776))]$

$= 74$ k-in$=6.17$ k-ft

From three point bending test: span 50 inch

$P_n = 4\ M_n /$ span

$= 4 \times 74/50$

$= 5.92$ kip

Hence, Maximum load and resisting moment from theory are 5.92 kip and 6.17 kip-ft

Table I-2 Maximum (Exptl./Theor) load (moment) ratios for non wrapped beams

Temp (F)	Beam	Age (months)	Wrap* Type	Max load (Exptl.) (kips)	Max moment (Exptl.) (kip-ft)	Max load (Theor.) (kips)	Max moment (Theor.) (kip-ft)	Max load ratio (Exptl./Theor)	Avg Max load ratio (Exptl./Theor)
room	Non aged 1	0	without-wrap	6.11	6.36	5.92	6.17	1.032	1.012
	Non aged 2			5.87	6.12	5.92	6.17	0.992	

Table I-3 Maximum load/deflection, Maximum (Exptl./Theor) load ratio and deformability factor for non-wrapped beams

Type	Beam	Age (months)	Wrap* Type	Max load (Exptl.) (kips)	Max def (Exptl.) (in)	Max load ratio (Exptl./Theor.)	Deformability (A_u/A_e)
room	Non aged 1	0	without-wrap	6.11	0.754	1.032	10.93
	Non aged 2			5.87	0.833	0.992	10.47

Table I-4 Loads at different limiting deflection values of non-wrapped concrete beams

Temp (F)	Beam	Age (months)	Wrap* Type	Load at standard deflection limit (kips)		
				1/360 (0.1667 in)	1/240 (0.250 in)	1/180 (0.333in)
room	Non aged 1	0	Without wrap	4.01	4.83	5.26
	Non aged 2			3.85	4.50	5.02

Table I-5 Average ratio of load at serviceability deflection to maximum load

Temp (°F)	Avg. ratio of load at deflection (span/360) to Max load	Avg. ratio of load at deflection (span/240) to Max load	Avg. ratio of load at deflection (span/180) to Max load
	Aging duration (months)	Aging duration (months)	Aging duration (months)
	0	0	0
room	0.656	0.779	0.858

Table I-6Load at crack width limit (0.016 in) of non-wrapped beams

Temp (F)	Beam	Age (months)	Wrap* Type	Load at limiting crack width(0.016 in) (kips)	Load at limiting crack width (0.016in) to max load
room	Non aged 1	0	Without wrap	3.8	0.622
	Non aged 2		Without wrap	3.9	0.664

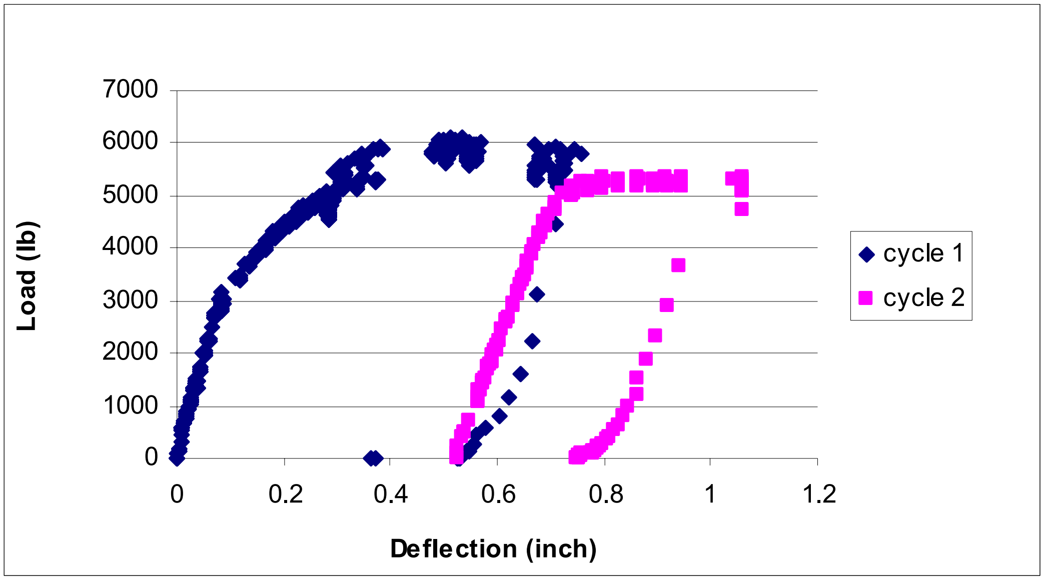

Fig I.2 Load-deflection curve of non-wrapped beam 1

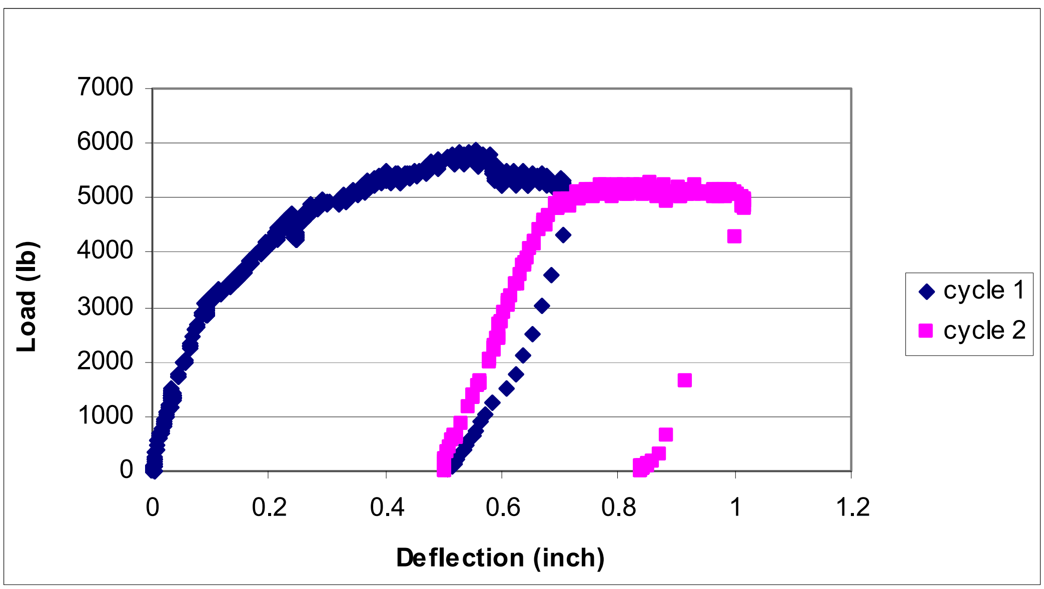

Fig I.3 Load-deflection curve of non-wrapped beam 1

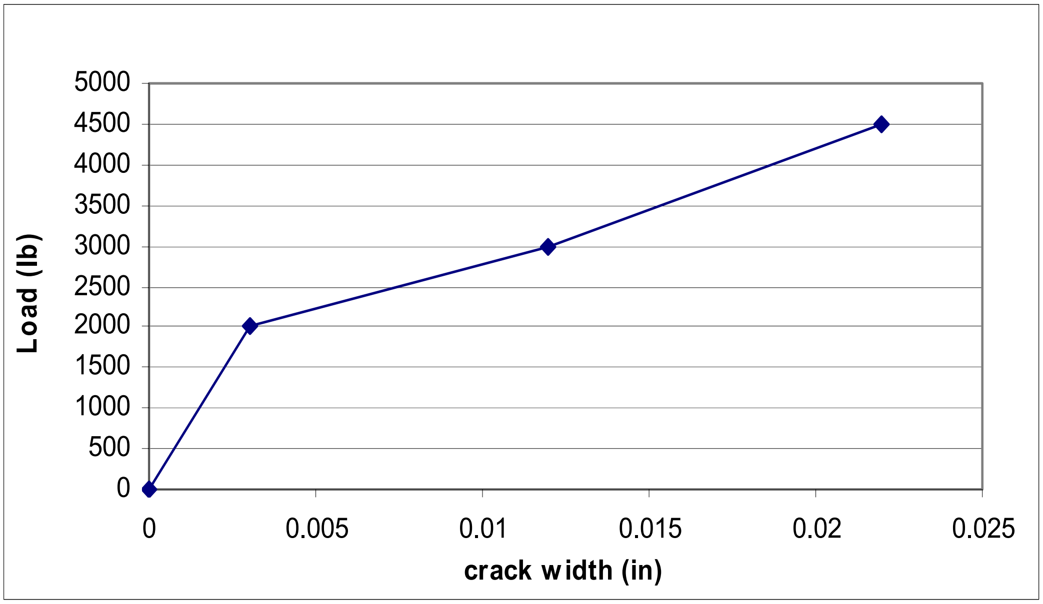

Fig I.4 Load-deflection curve of non-wrapped beam 1

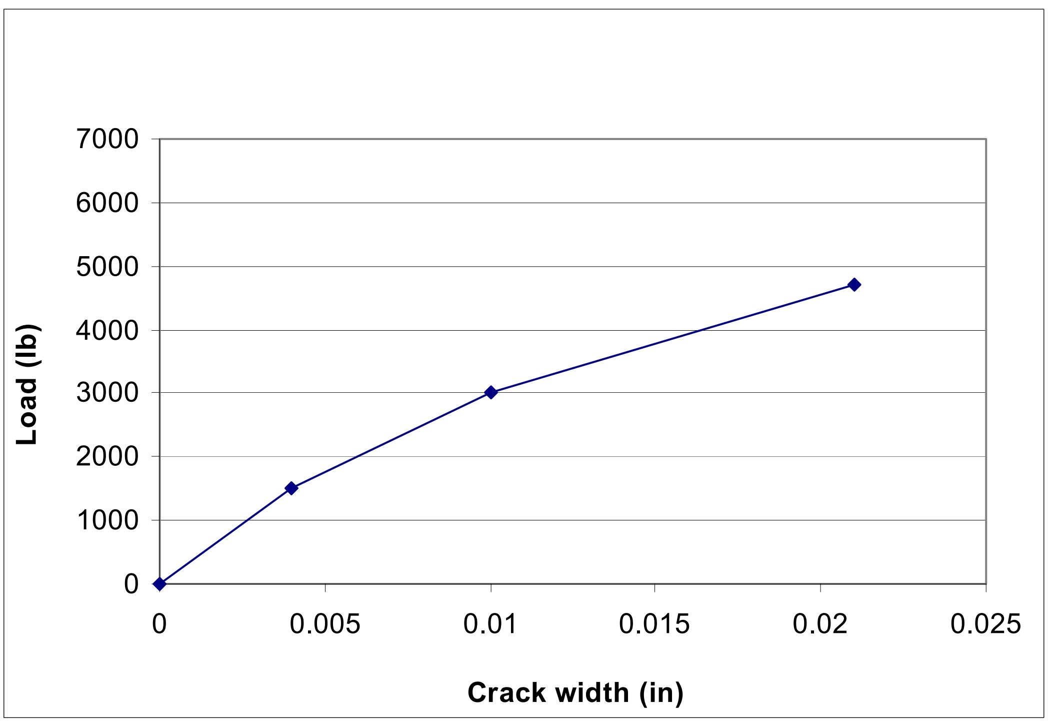

Fig I.5 Load-deflection curve of non-wrapped beam 2

Durability of Concrete Beams with FRP Wraps

Woraphot Prachasaree

Thesis submitted to the
College of Engineering and Mineral Resources
at West Virginia University
in partial fulfillment of the requirements for the degree of

Master of Science
in
Civil Engineering

Department of Civil and Environmental Engineering

APPROVAL OF THE EXAMINING COMMITTEE

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Udaya Halabe, Ph.D.

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